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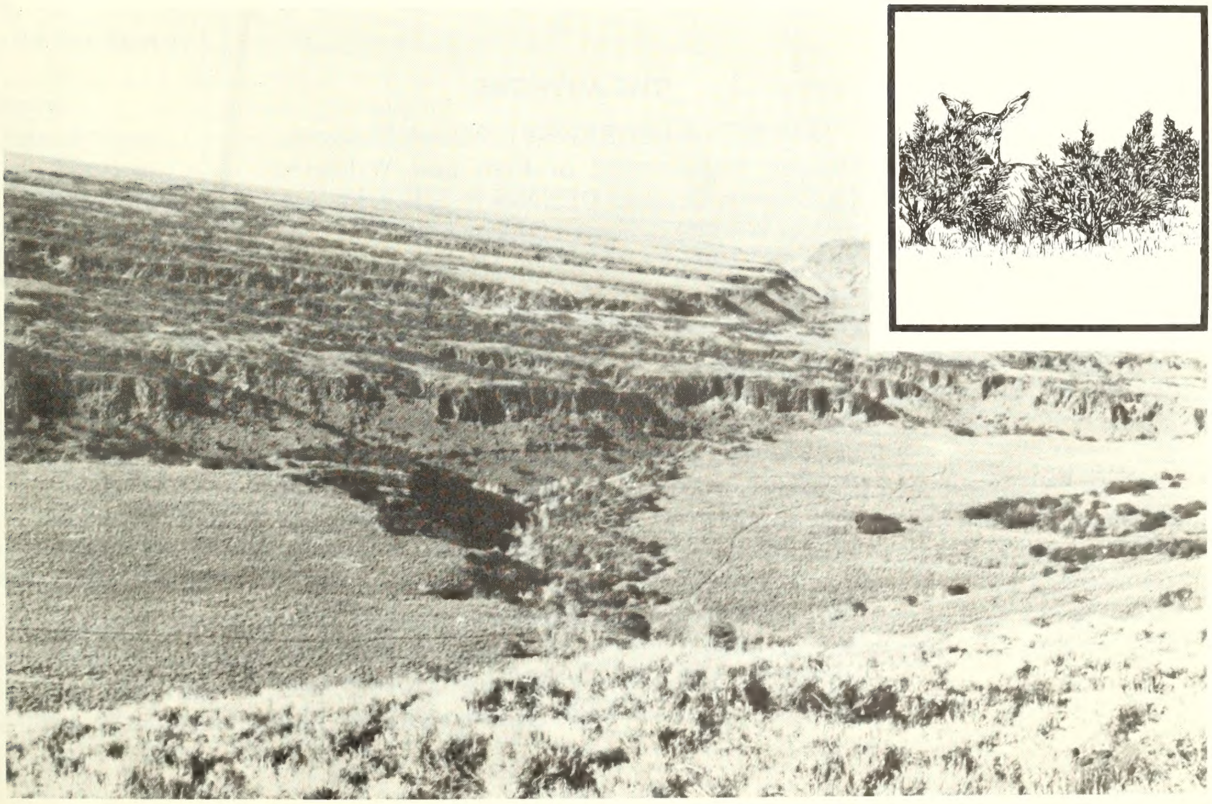
# WILDLIFE HABITATS IN MANAGED RANGELANDS-- THE GREAT BASIN OF SOUTHEASTERN OREGON

## MULE DEER

Donavin A. Leckenby
Dennis P. Sheehy
Carl H. Nellis
Richard J. Scherzinger
Ira D. Luman
Wayne Elmore
James C. Lemos
Larry Doughty
Charles E. Trainer



PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE U. S. DEPARTMENT OF AGRICULTURE

## ABSTRACT

Relationships of mule deer behavior and physiology to management of shrub-steppe plant communities in the Great Basin of southeastern Oregon are presented for application in land-use planning and habitat management. Communities are considered as they are used by mule deer for thermal cover, hiding cover, forage, fawning, and fawn rearing.

KEYWORDS: Deer (mule), wildlife habitat, range management, Oregon (Great Basin).

## THE AUTHORS

DONAVIN A. LECKENBY is Wildlife Biologist, Oregon Department of Fish and Wildlife, La Grande, Oregon. DENNIS P. SHEEHY is a former Wildlife Biologist, Oregon Department of Fish and Wildlife, Wallowa, Oregon. CARL H. NELLIS is Wildlife Biologist, Idaho Fish and Game Department, Jerome, Idaho. RICHARD J. SCHERZINGER is Wildlife Biologist, Oregon Department of Fish and Wildlife, Portland, Oregon. IRA D. LUMAN is Wildlife Biologist, Bureau of Land Management, Portland, Oregon. WAYNE ELMORE is Wildlife Biologist, Bureau of Land Management, Prineville, Oregon. JAMES C. LEMOS is Wildlife Biologist, Oregon Department of Fish and Wildlife, Hines, Oregon. LARRY DOUGHTY is Wildlife Biologist, Bureau of Land Management, Pinedale, Wyoming. CHARLES E. TRAINER is Wildlife Biologist, Oregon Department of Fish and Wildlife, Hines, Oregon.

This publication is part of the series **Wildlife Habitats in Managed Rangelands—The Great Basin of Southeastern Oregon**. The purpose of the series is to provide a range manager with the necessary information on wildlife and its relationship to habitat conditions in managed rangelands in order that the manager may make fully informed decisions.

The information in this series is specific to the Great Basin of southeastern Oregon and is generally applicable to the shrub-steppe areas of the Western United States. The principles and processes described, however, are generally applicable to all managed rangelands. The purpose of the series is to provide specific information for a particular area but in doing so to develop a process for considering the welfare of wildlife when range management decisions are made.

The series is composed of 14 separate publications designed to form a comprehensive whole. Although each part will be an independent treatment of a specific subject, when combined in sequence, the individual parts will be as chapters in a book.

Individual parts will be printed as they become available. In this way the information will be more quickly available to potential users. This means, however, that the sequence of printing will not be in the same order as the final organization of the separates into a comprehensive whole.

A list of the publications in the series, their current availability, and their final organization is shown on the inside back cover of this publication.

**Wildlife Habitats in Managed Rangelands—The Great Basin of Southeastern Oregon** is a cooperative effort of the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, and United States Department of the Interior, Bureau of Land Management.

## Introduction

Wildlife biologists, planners, resource managers, and interested citizens are increasingly involved in planning and allocating uses of public lands. Planning uses of rangeland often requires predicting effects of management on the habitat of mule deer, *Odocoileus hemionus*. Our objective is to describe optimum habitat for mule deer and provide information to help managers predict the consequences of range management alternatives on deer.

Shrub-steppe rangelands are normally managed to increase forage for livestock, but not intentionally managed to either create or maintain vegetative structure compatible with deer needs. Good livestock management—contrary to conventional wisdom—is not always good deer management. Changes in habitat can be made to benefit mule deer or to attain other goals, if such changes are compatible with the site capability (Baker and Frischknecht 1973; Crawford 1975; Hill 1956; Julander 1962; Leckenby 1968, 1970, 1978a; Leopold 1933; Plummer et al. 1968; Reynolds 1964, 1974; Robinette et al. 1952; Thomas et al. 1976, 1979; Tueller 1979; Tueller and Monroe 1975; Verme 1965). Benefits to deer depend on how compatible range management systems are with the physiological and behavioral needs of deer. The key to deer management is habitat management. Habitat is also affected by other range uses, such as agriculture, housing, and recreation. Although meeting projected demands for red meat will require more intensive livestock management (Forest-Range Task Force 1972, USDA Inter-Agency Work Group on Range Production 1974), this need not increase competition between livestock and deer for forage. Livestock grazing can be manipulated to make nutritious food available to wild ungulates at critical times (Anderson and Scherzinger 1975, Bell 1971, deBoer 1970, Leckenby 1968, Willms et al. 1980). Range seedings, of crested wheatgrass[1] for example, can increase forage diversity and maintain cover distributions if extensive monocultures are avoided.

Shrub-steppe ranges generally occur where annual precipitation is below 37.5 centimeters (15 inches) and are characterized by severe climate. Disturbance of vegetation initiates slow successions that do not regain original conditions even when areas are excluded from livestock grazing for up to 30 years (Rice and Westoby 1978, Robertson 1971). Because of the severity of such sites, some induced successional stages have lasted many decades.

Resident deer herds occupy some shrub-steppe ranges the year around. Other migratory herds spend only winters there, causing high animal concentrations on a small portion of the annual range. On such ranges the effects on deer of habitat manipulations are magnified.

Our objectives are to: (1) define optimally productive deer habitat on managed shrub-steppe rangelands; (2) tie deer habitat to plant community and structure; (3) apply these concepts to deer habitat management units; (4) compare consequences of habitat management to deer; and (5) present information that can be used in preparing environmental analyses, habitat management plans, allotment management plans, environmental impact statements, and long-range management plans.

The use of livestock grazing to improve mule deer habitat requires an understanding by resource specialists, managers, and administrators of the habitat requirements of deer and the effects of livestock grazing on deer habitat. The key to this understanding, and to communication about deer, is the common knowledge these specialists have about plant communities.

Understanding of plant communities, their structure, and arrangement in time and space can simplify discussions of the relationships of deer to their habitat. This is also basic to understanding interactions of ecological factors, evaluating their relative influences, and predicting the results of manipulation.

The relationships between deer and their habitat and the consequences of management actions described here apply primarily to the Great Basin of southeastern Oregon—specifically the Lake and Owyhee Desert sections (Holmgren 1972:78-87). The information may

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[1] Common and scientific names and their sources are listed in the appendix.

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apply generally to similar areas because: (1) much, generally consistent, data is available on mule deer–habitat relationships; (2) shrub-steppe communities are similar; (3) enhancement of livestock grazing dominates land management activities on most ranges; and (4) the basis for management of mule deer habitat is interpreting deer requirements in terms of plant community composition and structure. Extension of our rationale to other geographic areas must be done with caution and by incorporating applicable principles to new data and new knowledge about relationships of deer to habitat for those places.

This chapter is not a techniques manual, a compendium of treatment prescriptions, nor an evaluation of research publications. It is an examination of habitat relationships. We define cover and forage components of optimum deer habitat and describe how changes in plant community structure and composition affect habitat quality.

While we emphasize optimum habitats that allow deer herds to approach maximum productivity, we recognize that deer exist where habitats are less than optimum. We believe that deer habitats on shrub-steppe ranges can be improved by using livestock grazing as a management tool.

The literature and cumulative knowledge concerning deer is extensive and provides several ways to evaluate deer habitat. To narrow these possibilities and to achieve our objectives, we have made the following assumptions:

1. Manipulation of vegetation to benefit livestock is the primary practice that affects deer habitat and will increase as demands for red meat increase.
2. Resource allocations and management influence the welfare and productivity of deer.
3. Cover, forage, water, and space are required by deer.
4. Cover and forage areas are separable habitat components.
5. The diversity, size, arrangement, juxtaposition, and edges of cover and forage areas can be manipulated to achieve predictable changes in deer use and productivity.
6. While deer use the best cover and forage available, the closer to optimum the size, arrangement, and diversity of habitats the higher productivity will be.
7. Herd size is limited by the productivity of plant communities.
8. In situations where forage or cover are limiting deer productivity, and there is competition with livestock, we will consider deer needs first and pinpoint how deer habitat can be enhanced by appropriate livestock grazing systems.
9. Since behavior and tradition largely control deer distribution and movement (Gruell and Papez 1963; Leckenby 1977, 1978a; Mackie 1970; Severinghaus and Cheatum 1956; Zalunardo 1965) and prevent subpopulations of deer from leaving home ranges for adjacent forage and cover, the appropriate management unit is a deer subpopulation range.
10. Range treatments produce both immediate, obvious impacts on habitat and long-term, subtle impacts.
11. The plant community is a more obvious and sensitive indicator of present and past environments than combined measures of temperature, insolation, soil, etc. (Daubenmire 1968; DeVos and Mosby 1969; Duffey and Watt 1971; Leckenby 1968, 1970, 1977; Mueller-Dombois and Ellenberg 1974; Roberts 1975).

## MANAGEMENT UNITS

Sizes of habitat management units vary with management goals and whether they are based on biological or political grounds, or both. Existing political units, such as States, National Forests, Ranger Districts, and counties can be convenient for administration but are too large for management of deer habitat. Herd ranges, usually defined by a combination of natural and administrative boundaries (Dasmann 1971, Hunter and Yeager 1956), or seasonal ranges, defined by drainages, ridgelines, or roads, permit increased administrative sensitivity to deer needs, but both are too large to allow managers to identify and monitor specific habitat conditions. The largest unit that is administratively practical and, at the same time, sufficiently sensitive to deer-habitat relationships is the range of a subpopulation. A subpopulation is an aggregation of two types of social groups that occupy a specific area: females with fawns and adult males. A subpopulation range encompasses the separate home ranges of several groups of does with fawns and groups of bucks.

Since our objective is to define optimum habitat for deer, we have adopted the subpopulation range as the most appropriate management unit and use it in this publication. It is large enough to be administered effectively yet small enough to allow monitoring of deer responses to habitat. Subpopulation ranges are large enough to accommodate livestock grazing allotments, allow manipulation of cover and forage areas over time, and suit pasture rotation designs; yet they are also small enough that two or more can be combined as a larger element of a coordinated management plan.

Subpopulation ranges are usually 10 to 20 times larger than seasonal home ranges of individual deer, which range from 50 to 1 240 hectares (120 to 3,060 acres) and average 260 hectares (640 acres) in widely different habitats (Dasmann 1971, Leckenby 1978b, Leopold et al. 1951, Robinette 1966, Rodgers et al. 1978, Swank 1958, Taber and Dasmann 1958, Zeigler 1978). On steep slopes, ranges of subpopulations appear as corridors. For example, a "subpopulation of the Middle Park deer herd" wintered on Cedar Ridge in an area 6.4 by 1.6-3.2 kilometers (4 by 1-2 mi) (Gilbert et al. 1970:17, 20). A California deer herd consisted of two subpopulations; the average area occupied was 347 $km^2$ (134 $mi^2$) in summer and 47 $km^2$ (18 $mi^2$) in winter (Leopold et al. 1951:16-19, 49). A subpopulation occupied a corridor about 5 by 10 kilometers (3 by 6 mi) on a shrub-steppe winter range (Leckenby 1978b).

In southeastern Oregon, habitat management units between 2 500 and 4 700 hectares (6,400 to 11,520 acres) approximate subpopulation ranges. These units appear either as corridors on sloping range, about 5 by 10 kilometers (3 by 6 mi), or as blocks on more level range, about 8 to 9 kilometers (5 to 6 mi) on a side. These sizes represent a compromise between maximum sensitivity to deer biology and minimum administrative cost. The number of deer in a subpopulation varies widely with quality of habitat and can range from as low as 20 deer up to 2,000.

## PLANT COMMUNITIES AND STRUCTURAL CONDITIONS

Plant communities may be grouped in various ways for different management purposes. We identify groups by dominant plant species (Dealy et al. 1981). We have arranged the multitude of plant communities and seral stages in shrub-steppe succession into five structural conditions:[2] grass-forb, low shrub, tall shrub, tree, and tree-shrub.

### Use of Plant Communities by Deer

Deer usually require several plant communities. Daily and seasonally, they use a variety of land and vegetation features for cover and forage. Some communities are used only part of each season, but most communities contribute to the well-being of deer sometime during the year. When deer can meet their needs within a relatively small area, deer productivity will be enhanced because maintenance energy costs will be less (Moen 1968b).

Migratory deer use plant communities on three seasonal ranges (Zalunardo 1965). They migrate from lower elevation winter ranges through spring-fall ranges to higher summer ranges (fig. 1). Fawning usually occurs in upper spring-fall and summer ranges. Most deer gradually disperse over the summer range as snow recedes to higher elevations.

Fall migration is largely influenced by weather. Severe storms often precede migration to winter range. In moderate winters, deer may not move to winter range at all, or they may arrive only after spring growth of forage.

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[2] Maser, C., and J.W. Thomas. The relationship of terrestrial vertebrates to the plant communities and structural conditions. Unpublished data on file at Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

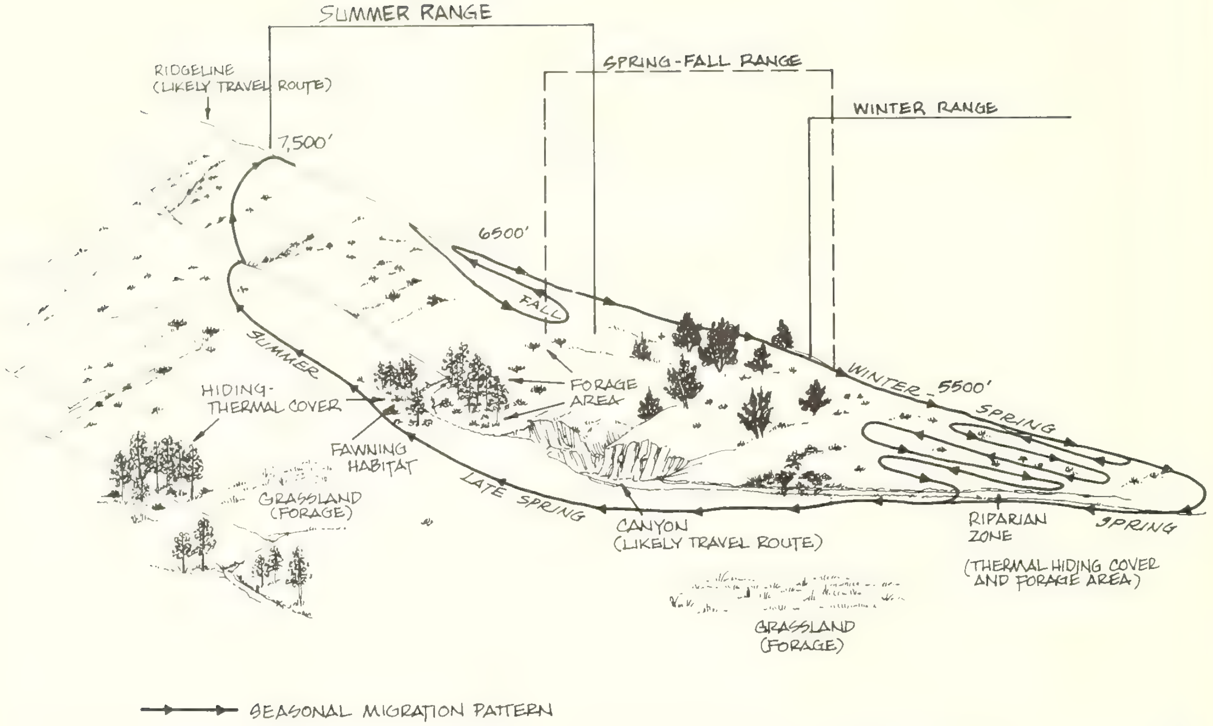


Figure 1. — Use of seasonal ranges depends on how well deer requirements are met by sizes and distribution of habitats relative to ridgelines, canyons, slopes, and flats.

## Management Based on Plant Communities and Structure

The number of deer a management unit can sustain is determined partly by the structure, composition, and arrangement of the vegetation, habitat diversity, amount of edge, availability of water, soil productivity, and weather severity. Through manipulation of vegetation structure and composition, habitat diversity, amount of edge, and availability of water land managers can influence the ability of the land to produce deer.

Plant communities, structural conditions, and land features provide the information managers need to predict responses of both animals and vegetation to management and provide a basis for land-use planning (Crawford 1975, Daubenmire 1968, DeVos and Mosby 1969, Mueller-Dombois and Ellenberg 1974). This information includes:

1. Current composition and structure of the vegetation;
2. Soil depth, stability, and suitability for fertilization;
3. Elevation, steepness, position, aspect, shape, and length of slopes;
4. Present type of use by deer and livestock;
5. Past uses for roads, fences, water sources, and grazing;
6. Probable results of treatment and potential effects on productivity.

Deer production is usually greatest in the shrub and tree-shrub structural conditions (Hill 1956, Leopold 1950, Moen 1973). Structural condition can be retarded or advanced by grazing, fire, chemicals, or machinery (Koehler 1975, Plummer et al. 1968, Roberts 1975, Valletine 1971, Willms et al. 1980, Yoakum and Dasmann 1969). The challenge is to plan diversity of habitat and interspersion of cover with forage that will enhance or maintain deer habitat within each subpopulation management unit in areas managed primarily for livestock grazing.

## Habitat Requirements of Mule Deer

Optimum habitat for deer is defined as the amount and arrangement of cover and forage areas which result in the greatest use of the most area. Optimum habitat is described here by sizes of stands and their arrangements in time and space to meet needs of deer for thermal and hiding cover, forage areas, and fawning and fawn-rearing habitat.

Range use by deer is not uniform. Habitat conditions often vary between intensively and lesser used areas (Bertram and Rempel 1977, Leckenby 1978b, Owen 1980, Webb 1948). Just how variations in use are related to conditions is not always clear.

### COVER

Deer require protection from weather and predation. Because of the usual structure of shrub-steppe communities, where thermal cover is provided, hiding cover is usually also provided (fig. 2). On most range sites, cover is provided primarily by tall shrub species, which in some seasons also provide much of the deer forage. On some management units, cover needs may be satisfied by one plant community, juniper/sagebrush, for example.

#### Thermal Cover

We define optimum thermal cover for deer within the Great Basin of southeastern Oregon as stands of evergreen or deciduous trees or shrubs, at least 1.5 meters (5 ft) tall, with crown closure greater than 75 percent. Deer will use the best available thermal cover, although it may not be optimum (fig. 3). Structure of vegetation is more important than composition, and levels of crown closure greater than 75 percent appear equally preferred. Thermal cover should be at least 0.8-2 hectares (2-5 acres), since the area of thermal protection increases with stand widths greater than 90 meters (300 ft).

The quality of thermal cover for deer is affected by the following factors and relationships:

1. Net radiation flows are modified by crown closure.
2. Snow depth decreases as crown closure increases.
3. Vegetation taller than deer furnishes diminishing benefits.
4. Sixty-percent crown closure meets minimal year-round needs.
5. Production is greater where there is protection from effective temperatures outside the thermal neutral zone.

Figure 2. — Shrub-steppe plant communities that provide thermal cover usually provide hiding cover also.

These relationships have been observed by Dasmann (1971), Leckenby (1977), Loveless (1964), and Moen (1968b, 1973). The zone of thermal neutrality (Brody 1945, Holter et al. 1975) is that range of temperatures over which an animal's metabolic rate, as measured by heat production, is minimal.

Effective temperature is the result of the combined effects of several factors including air temperature, wind speed, and radiation (Moen 1968b, Porter and Gates 1969). Wind chill (Siple and Passel 1945) is an example of effective temperature derived from air temperatures and wind speeds only.

Deer use evergreen trees and shrubs for thermal cover on winter range and deciduous trees and shrubs as well on summer and spring-fall range (Leckenby 1977, 1978a; Loveless 1964, 1967; Mackie 1970). Topographic features such as rocky bluffs enhance the thermal cover offered by vegetation in some locations and may provide the only thermal cover (Grace and Easterbee 1979, Staines 1976).

Thermal cover allows deer to conserve energy by protecting them from stresses induced by weather. Energy in excess of that required to maintain basal metabolism, regulate temperature, and provide for tissue replacement and necessary activity is then available for productive processes.

Much of the energy in the food of ruminants is used to satisfy basal and maintenance requirements or is lost in waste products. Basal requirements are those necessary to sustain life. These include maintaining minimum body temperature and heart rate. Maintenance requirements are in addition to basal requirements and include travel to and from food and water and replacement of hair coats. If

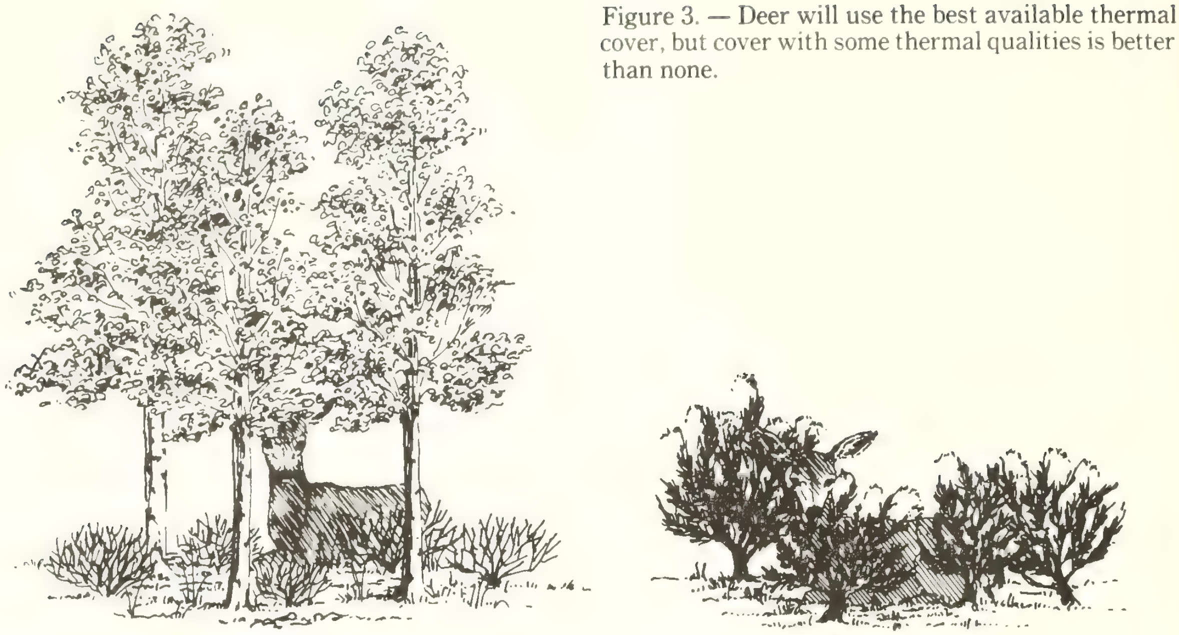
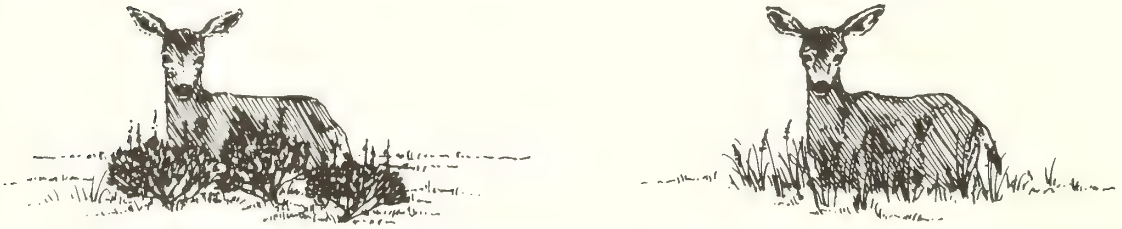


Figure 3. — Deer will use the best available thermal cover, but cover with some thermal qualities is better than none.

A. OPTIMUM THERMAL COVER,
ALL AROUND BEST (TREE AND SHRUB)

B. SECOND BEST (TALL SHRUB)



C. LITTLE THERMAL PROTECTION
(SHORT SHRUB)

D. NONE TO LEAST THERMAL PROTECTI
(GRASSLAND)

basal requirements are not met the animal will die; if maintenance needs are not met the animal will lose body weight. When basal and maintenance needs are met, energy surpluses are used for production, which includes growth, storage of reserves, reproduction, and care of young (Blaxter 1962; Brody 1945, 1956; Findlay 1954; Grace and Easterbee 1979; Holter et al. 1975; Mitchell 1962; Moen 1968b, 1968c, 1973; Nordan et al. 1970; Ozoga and Gysel 1972; Silver et al. 1969 and 1971).

Temperature regulation in response to thermal stress increases the energy cost of maintenance (fig. 4) and thus takes energy that otherwise could be used in productive processes. Maintenance requirements increase when radiation flows, surface temperatures, air temperatures, wind speeds, and snow depths increase flows of energy **from hot** environments **to** ruminants as well as **from** ruminants **to cold** environments (Chappel and Hudson 1978; Holter et al. 1975; Malechek and Smith 1976; Moen 1968a, 1976; Porter and Gates 1969). In attempts to reduce maintenance costs, deer may remain quiet under thermal cover or may move to cover from open areas that offer only low-energy forage but greater thermal stress (Leckenby 1977, Loveless 1964, Ozoga and Gysel 1972). If their diet meets or exceeds maintenance requirements, however, deer and cattle may bed or stand in exposed forage areas during periods of thermal stress (Malechek and Smith 1976; Moen 1968a, 1968c).

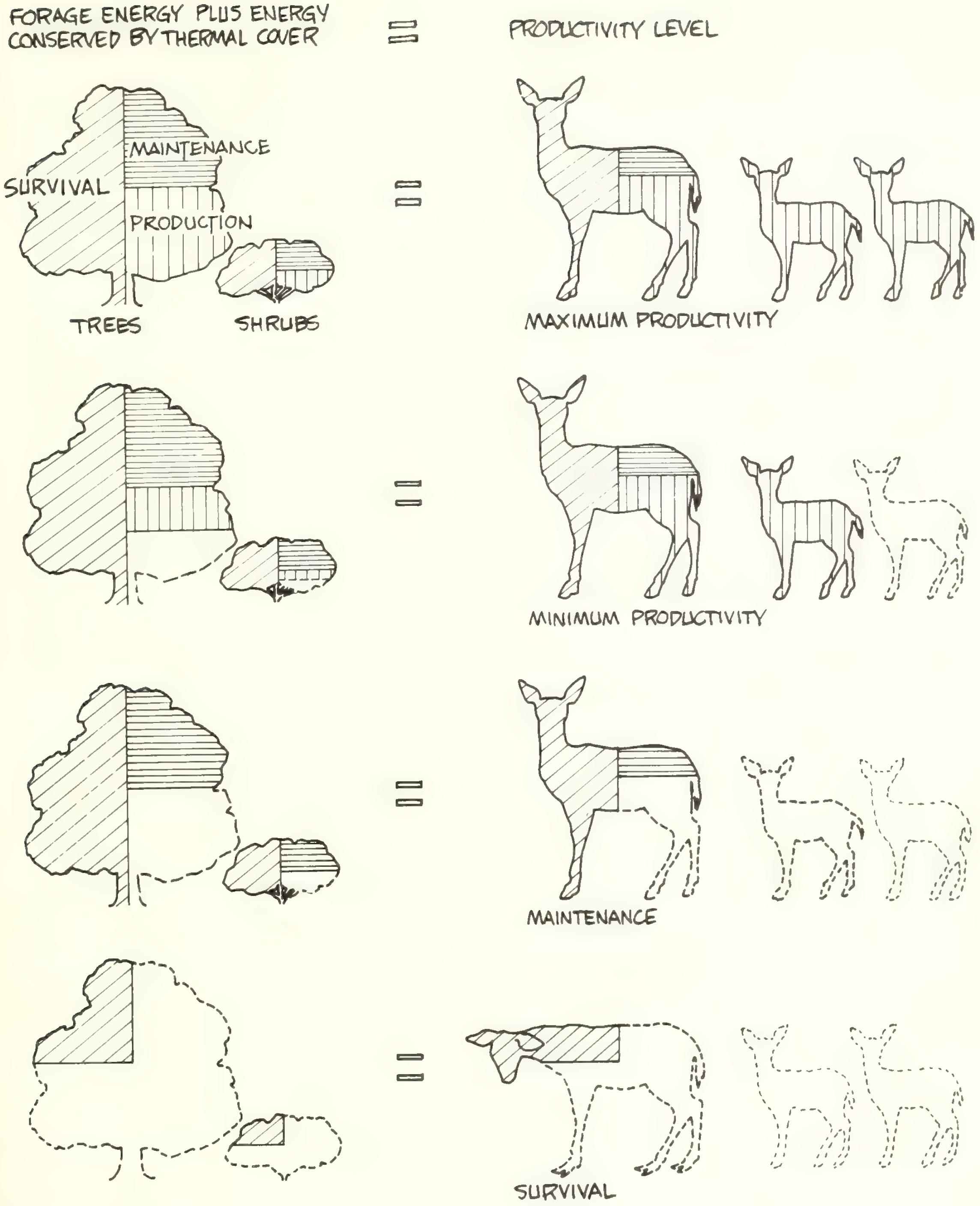


Figure 4. — Productivity of deer varies with the supply of energy available from forage and the thermal cover to conserve it. When quality and quantity of forage and cover is minimal, only survival needs are met. With increasing supplies of both, animals can maintain body weights. As supplies increase further, growth can occur, reserves of fat can be stored, and does can produce fawns and milk.

The thermal neutral zone covers a range of temperatures over which heat production increases only slightly. With temperatures outside that zone, metabolic rate increases rapidly (Blaxter 1962, Brody 1945, Chappel and Hudson 1978, Holter et al. 1975, Moen 1968b). For domestic animals, the shelter and food usually provided the year around broadens the thermal neutral zone, increasing the upper and reducing the lower critical temperatures (Blaxter 1962:116-146). Brody (1945:305-306) suggested that productive efficiency of domestic animals was little affected by temperatures ranging from near zero (18°C) to about 80°F (27°C). The shelter and food available to wild ruminants, however, over much of the year reduces the thermal neutral zone to a narrower range of temperatures.

The thermal neutral zone of white-tailed deer in captivity has been examined in different seasons. A "comfort zone" between 5°C and 20°C (41°F and 68°F) has been suggested for winter, since the estimated minimum level of energy expenditure occurred at about 12°C (54°F), but a thermal neutral zone could not be demonstrated for spring, summer, or fall (Holter et al. 1975). In another study, deer in winter coat increased heat production by only 25 percent at temperatures between 0°C and 20°C (32°F and 68°F), but when the temperature was dropped to -15°C (+5°F) a 75-percent increase was seen (Silver et al. 1971).

The cooling effect of wind may either increase or decrease thermal stress. Winds coupled with temperatures below the thermal neutral zone intensify stress due to cold because the effective temperature is reduced by convective cooling (Grace and Easterbee 1979, Porter and Gates 1969, Siple and Passel 1945, Staines 1976, Stevens and Moen 1970). At temperatures above the thermal neutral zone, winds lower effective temperatures and reduce stress from heat.

Effects of radiation, humidity, and snow on flows of energy to and from wild animals are also of great biological importance (Gilbert et al. 1970; Grace and Easterbee 1979; Moen 1968b, 1973, 1974; Moen and Jacobson 1974; Porter and Gates 1969).

Vegetation structure helps create microclimates. Height, canopy closure and depth, and stem density modify temperature, wind speed, precipitation, and radiation within stands. Reifsnyder and Lull (1965:70) wrote "...the forest can reduce monthly maximum air temperature in the summer by about 10°F below that in the open, reduce annual rainfall (through interception) by 15 to 30 percent, and reduce wind velocities by about 20 to 60 percent." Canopy closure in thermal cover reduced snow depths from 10 to 50 percent of that in shrublands (Leckenby and Adams 1978).

Structural effects have been quantified and can be related to the biology of deer (Bergen 1971, 1972, 1974; Cochran 1969; Gary 1974; Geiger 1966; Gifford 1973; Nudds 1977; Ozoga 1968; Ozoga and Gysel 1972; Reifsnyder and Lull 1965; Stevens and Moen 1970; Verme 1965). Shrub communities also influence microclimate, but less than forests.

Thermal protection is as important in summer as in winter. Lack of protection in summer not only reduces immediate productivity but also lowers reserves necessary for survival during the coming winter. Lack of protection in winter not only threatens immediate survival but also reduces productivity during the following summer. The importance of thermal protection in summer could not be fully appreciated until annual cycles in body weight of deer were documented (Robinette et al. 1973, Short et al. 1969, Silver et al. 1969, Wood et al. 1962, Wood and Cowan 1968).

Optimum microclimates for deer require more than 50-percent canopy closure (Verme 1965). Incoming and outgoing radiation will substantially increase or decrease surface temperatures at less than 50-percent closure. Canopy closures greater than 50 percent create more constant and less stressing microclimates by minimizing fluctuations of incoming and outgoing radiation. In the Great Basin, where temperatures are often outside the thermal neutral zone for deer, 60-percent canopy closure is the minimum criterion for thermal cover.

The severity of temperature, wind, precipitation, and radiation in forage areas surrounded by cover stands increases with the ratio of forage-area diameter to height of the adjacent cover stand; density of nearby cover has an important but smaller effect (Cochran 1969, Geiger 1966, Gifford 1973, Reifsnyder and Lull 1965, Verme 1965).

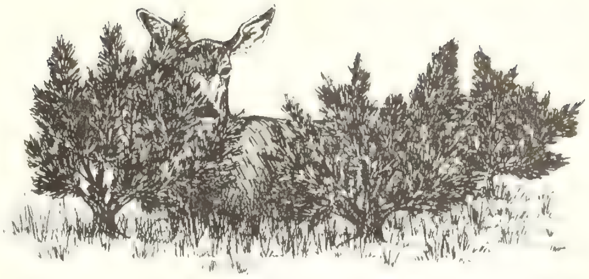
Riparian habitats in rangeland areas are extremely valuable for thermal cover and are used intensively by wildlife, livestock, and people. This habitat usually combines in a small area the vegetative and topographic components that together fulfill most deer requirements. Riparian zones also receive intensive livestock use because of the availability of thermal cover, green forage, and water. People prefer riparian habitats for fishing and water-oriented recreation. Thus, when thermal stress occurs, deer compete with other big game, livestock, and people for riparian zones.

### Hiding Cover

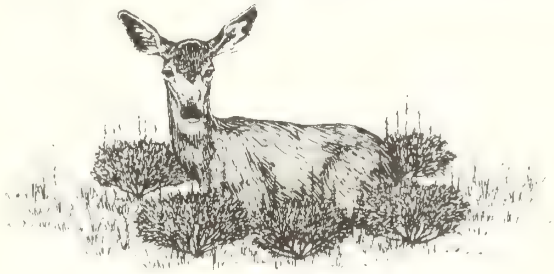
Managers assume that deer require hiding cover (also called escape or security cover by some authors) to make maximum use of a range (Bertram and Rempel 1977, Dasmann 1971, Nudds 1977, Owen 1980, Reynolds 1972). We define optimum hiding cover on shrub-steppe rangeland as vegetation at least 60 centimeters (24 inches) tall and capable of hiding 90 percent of a bedded deer from view at 45 meters (150 ft) or less (the sight distance after Thomas et al. (1979:109), figs. 5 and 6). Owen (1980) detected significant associations between visual density of vegetation and activities of free-ranging mule deer.

Sight distances differ between stands because of differences in plant characteristics and seasonal changes caused by plant phenology. Tall shrubs provide adequate hiding cover for some activities. Low shrubs often hide bedded fawns at less than 1.5 meters (5 ft) during summer. But both shrubs and trees are often required to hide deer against a snowy background at less than 800 meters (½ mi).

Areas of hiding cover should be between four and eight sight distances wide (190 to 380 meters or 600 to 1,200 ft). Patches of hiding cover as small as 2 to 10 hectares (6 to 26 acres) are probably sufficient for social groups of deer. Optimum distribution of hiding cover within a management unit consists of continuous, interconnecting zones and scattered patches (fig. 7). Canyons and ravines supplement and enhance vegetative hiding cover. Although topography may produce a visual barrier between an animal and a predator or a road and distance may improve security, deer may still feel vulnerable without vegetative cover. On short sagebrush and grass rangelands deer substitute distance and topography for vegetative cover. "Safe" distance varies with time of year, health and activity of the animal, and experience and conditioning of the animal to varied forms of disturbance and harassment. Although distance and topography, by definition, do not provide optimum hiding cover in large open areas, they may provide a partial substitute.



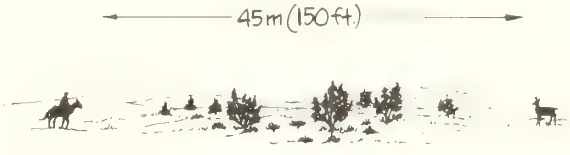
DEER 90 PERCENT HIDDEN AT 45m. (150 ft) IN MOUNTAIN BIG SAGEBRUSH



DEER 90 PERCENT VISIBLE AT 45m (150 ft) IN LOW SAGEBRUSH

Figure 5. — Vegetation that hides 90 percent of a bedded deer from view at 45 meters (150 ft) qualifies as hiding cover, provided the stand is at least 190 meters (600 ft) wide. Low shrub communities offer little hiding cover.

Figure 6. — The distance at which a deer is 90 percent hidden from view is defined as the "sight distance" (after Thomas et al. 1979). Hiding cover requires that sight distance be no more than 45 meters (150 ft).



ONE SIGHT DISTANCE

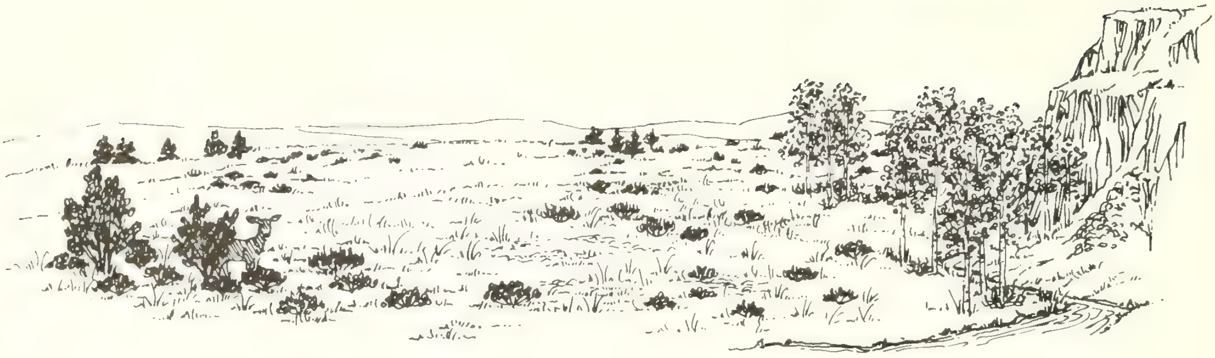


Figure 7. — Ideal mule deer range consists of a mosaic of plant communities arranged to provide thermal cover, hiding cover, and forage areas of optimum structure and size.

## FORAGE

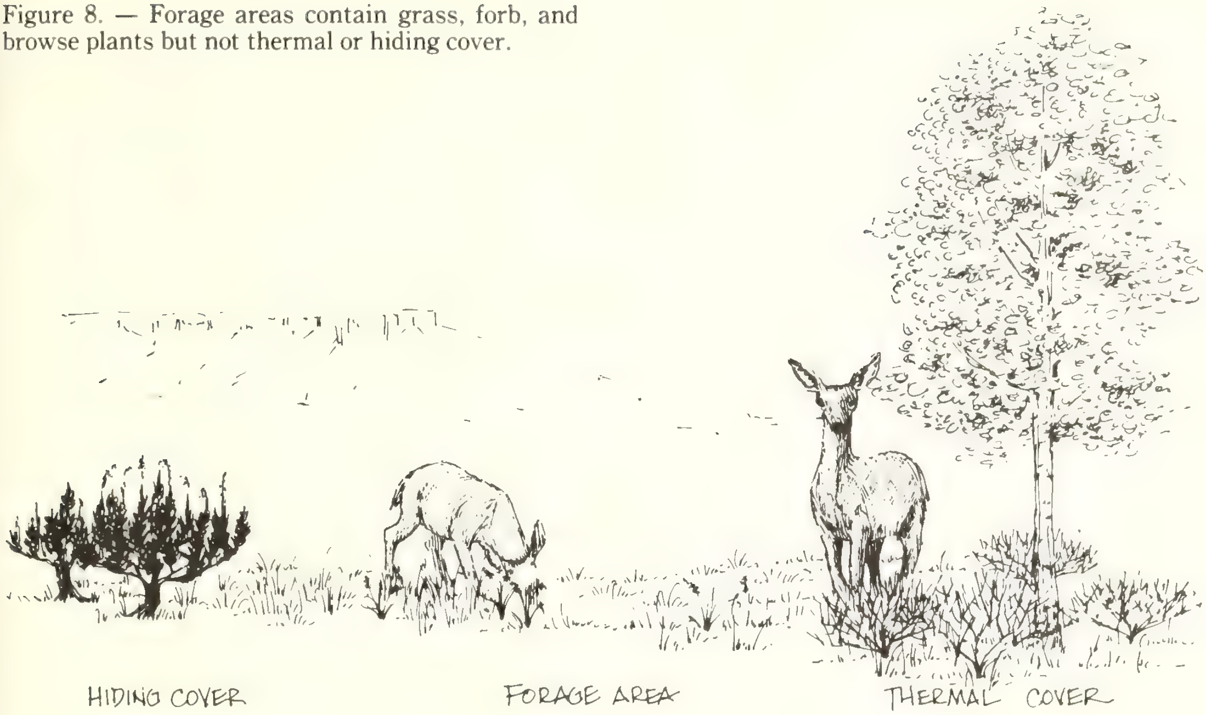
Forage areas are vegetation stands used by deer for grazing or browsing which do not fit the definitions of thermal or hiding cover (fig. 8). This definition assumes that optimum forage areas do not constitute optimum cover areas, although plant species that provide forage at one season often are used primarily for cover at other seasons. For example, big sagebrush and bitterbrush forage may satisfy survival or maintenance needs in fall and winter but are used primarily for cover in spring, when forb and grass species are available to meet maintenance and production requirements (Holl et al. 1979; Leach 1956; Leckenby 1978a, 1978c). Forage and cover types are seldom mutually exclusive on shrub-steppe rangelands, but such habitat division is useful for planning and management.

Livestock and deer often eat the same forage species but the overlap varies with range, season, and class of livestock. It is greatest if livestock and deer occupy the same range when young, green grass and forbs are prominent in the diet of both (Dusek 1975, Hansen and Clark 1977, Hansen and Reid 1975, Longhurst et al. 1979, Smith and Julander 1953). Such dietary overlap works to the advantage of management because livestock graze the cured grasses of species that deer also eat. Thus cattle grazing in summer exposes green forage for deer in fall, and winter grazing by cattle improves forage for deer in spring.

Grazing livestock on mule deer range at appropriate times minimizes direct competition for available forage and assures continued health of range plants. Fall grazing of livestock on deer summer range can be beneficial, provided deer have migrated from the area. Fall grazing by livestock on deer winter ranges can also be beneficial, provided it occurs before greenup and the arrival of deer. Maximum benefits will be realized if livestock remove little of the dormant browse. Spring turnout of livestock on deer winter range should occur following spring greenup and after most of the deer have migrated. It is critical that livestock be removed from deer winter range when soil moisture is still adequate to permit grasses to grow new leaves to replenish nutrient reserves in their roots. If livestock removal is delayed beyond this point, the vigor of forage plants will decline. Continued abuse of plants by such extended grazing will eventually reduce plant productivity, and declines in the productivity of both deer and livestock will soon follow.

Where annual grasses, such as some cheatgrass stands, persist in spite of continued attempts to convert them to native bunchgrass, it might be wiser and more economical to manage those sites for annual grasses instead of seeding them with exotic perennials. Permitting cheatgrass islands in expanses of sagebrush or crested wheatgrass would maintain greater forage diversity than reseeding entire blocks. Fall burning of cheatgrass stands can make nutritious growth available, but the hazards of erosion should be

Figure 8. — Forage areas contain grass, forb, and browse plants but not thermal or hiding cover.



considered. Young cheatgrass is nutritionally rich and it develops earlier in both fall and spring than many native perennials. It is very tolerant to intensive grazing. Because they mature rapidly, however, annual grasses also decline more quickly in forage value than perennial grasses.

The use deer make of forage areas depends on the size and interspersion of cover areas as well as size and arrangement of the forage areas. Deer do not fully utilize forage areas that are too far from cover (Reynolds 1962, 1964, 1966; Terrel 1973); they conserve energy by this strategy. Travel to cover and seasonal migration to more favorable ranges increases the amount of energy required for maintenance (Holl et al. 1979, Moen 1973, Wallmo et al. 1977). Forage areas wider than 250 meters (820 ft) create less than optimum conditions (fig. 9); walking requires from 18 to 67 percent of the energy expenditures of deer, elk, and pronghorns (Moen 1973:358-361). Appropriate arrangements of forage areas, thermal cover, and hiding cover can minimize energy losses caused by exposure, travel, and anxiety (figs. 7 and 10 are stylized examples). Exposure to thermal stress is most severe in openings with diameters more than five times the height of adjacent cover, and energy drain from movement and tension associated with alertness also increase with distance to cover. The production of muscle, fat, and milk and prospects for survival all decline (fig. 4) when energy, protein, carbohydrates, fats, and minerals from forage do not surpass maintenance requirements (Blaxter 1962; Brody 1945, 1956; Holl et al. 1979; Moen 1973; Sadleir 1969).

A diversity of plant species tends to maintain forage quality and availability over the seasons and to provide a buffer against plant losses to diseases or insects. Digestibility and nutrient content of forage are controlled by phenological stages of growth, recognized by changes in plant form—bud burst, leaf expansion, stem lengthening, and flowering (Hickman 1975; Hormay 1943, 1956, 1970; Hyder and Sneva 1963; McIlvanie 1942; Subcommittee on Feed Composition 1969). Quality generally declines with weathering and from spring through winter. The phenologically young leaves of most species contain approximately equivalent high levels of digestible nutrients (Subcommittee on Feed Composition 1969). Some species attain that stage only in spring; others also produce nutrient-rich foliage in fall.

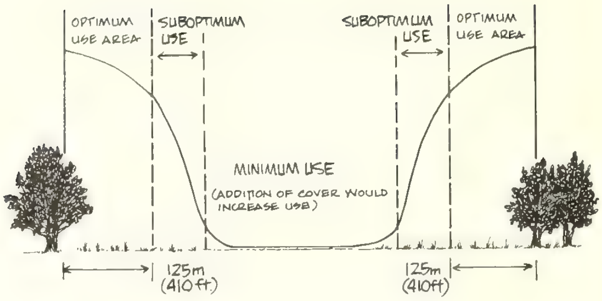
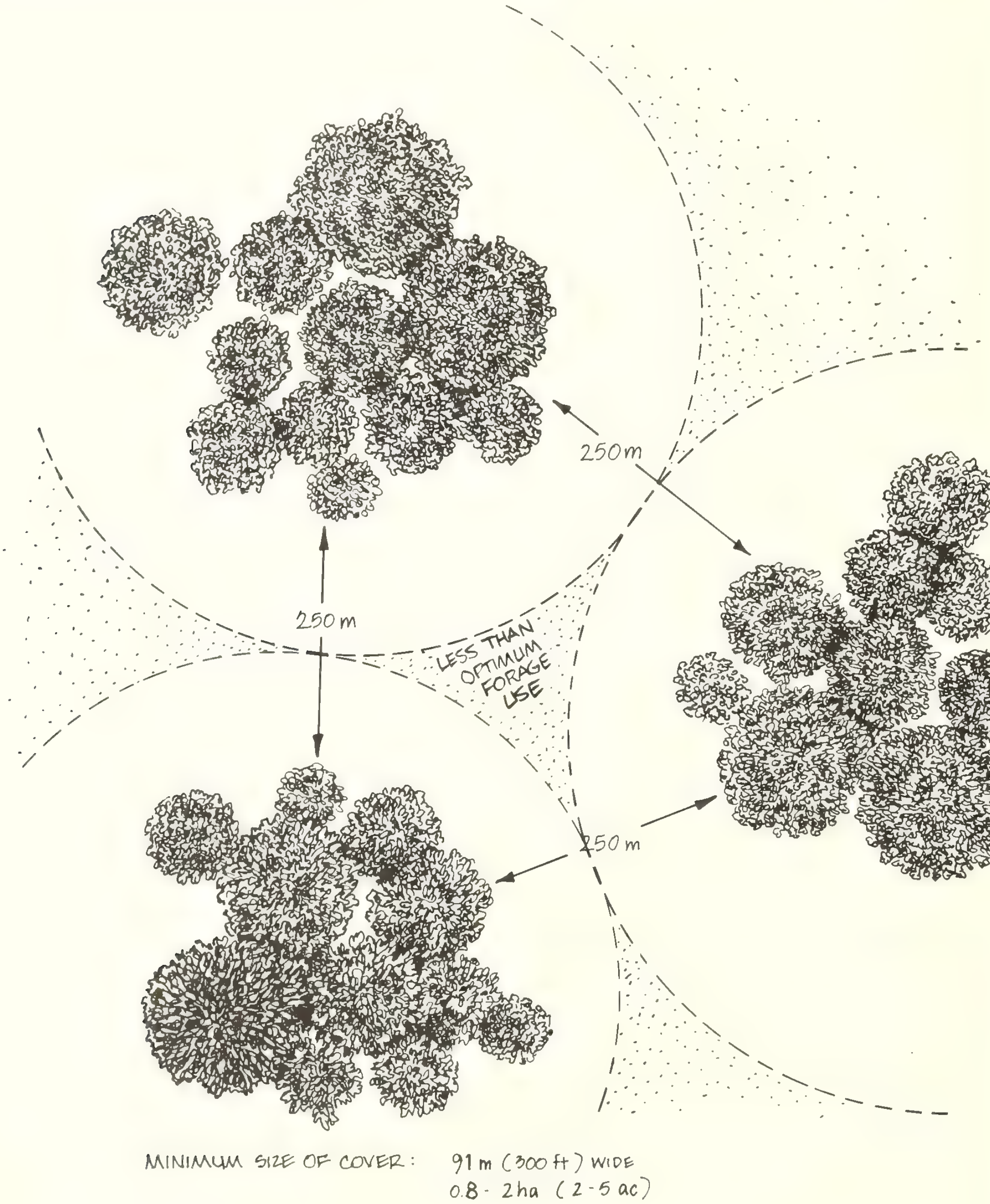


Figure 9. — Deer do not fully utilize forage areas that are more than 125 meters (410 feet) from cover.
Figure 10. — Centers of forage areas wider than 250 meters (820 ft), or 125 meters (410 ft) from cover edges, are used less than centers of smaller areas.


250m
250 m
250 m
LESS THAN OPTIMUM FORAGE USE
MINIMUM SIZE OF COVER: 91 m (300 ft) WIDE
0.8 - 2 ha (2 - 5 ac)

Deer of all ages need high quality, succulent food to recover from weather stress, replenish body reserves, and grow and reproduce at optimum rates. This is especially important to nursing does. Young plant tissue is required because only in the early stages of growth does it contain an optimum balance and high concentrations of maximally digestible nutrients needed to produce muscle, fat, and milk.

Deer and other ungulates have foraging habits tied to their physiological requirements for survival and reproduction and adapted to cycles of plant phenology. They cope with declining forage quality by selecting plants and plant parts that are phenologically younger (Bell 1971; deBoer 1970; Holl et al. 1979; Hungerford 1970; Leach 1956; Leckenby 1968, 1969, 1978a, 1978c; Spalinger 1980:106); thus they need a diversity of forage plant species that reach equivalent phenological ages at different times. For example, Sandberg bluegrass begins leaf growth in late winter and has flowered by late spring; bluebunch wheatgrass does not begin growth until late spring and flowers in midsummer.

Because grazing and burning affect the phenology of forage plants, appropriate management can prolong the availability of high quality forage for mule deer (Anderson and Scherzinger 1975; Leckenby 1968, 1978c; Tueller and Tower 1979; Willms et al. 1979, 1980).

## SPECIAL HABITAT NEEDS

### Fawning and Fawn-rearing

Compact areas that contain a diversity of thermal cover, hiding cover, succulent forage, and water are needed by does during fawning and fawn-rearing (Reynolds 1974, Sheehy 1978, Stuth 1975). These areas become their activity centers during fawning in spring and remain central to their movements during the fawn-rearing period of summer.

Fawning habitat consists of vegetation stands used by does during birth and by newborn fawns for a brief sedentary period of about 1 week. Although fawning occurs in various habitats and farther than 1 mile from trees,[3] optimum fawning habitat is an area of low shrubs or small trees taller than .7 meter (2.2 ft), with at least 40-percent canopy closure, that lies within 50 meters (160 ft) of taller tree cover. It is located on slopes of 0 to 30 percent and within plant communities where forage is succulent and plentiful in June (Sheehy 1978) (fig. 11).

In ideal fawning habitat of 2 to 10 hectares (5 to 26 acres), a doe expends only a minimum of energy to meet her daily requirements. Surplus energy can then be transferred, through milk, into fawn growth (fig. 4). Water should be available within 600 meters (2,000 ft). Elder (1956) surmised that succulent forage meets only marginal water requirements. The farther a doe has to range from her fawn to satisfy daily requirements for water or food, the more energy she expends and the less energy she has for milk production. A reduced supply of milk decreases fawn growth and jeopardizes fawn survival. Absence of the doe from the area in which the fawn is concealed also increases the potential for predation since the doe is frequently too far away to protect the fawn.

Although one doe requires a relatively small area, habitat for several does fawning at the same time must be larger. When the density of animals in optimum fawning areas is high and cover patches are converted to forage areas, does may be forced to use suboptimal habitats or accept crowding. Crowding causes strife between does and their actions probably attract and help predators locate hiding fawns.

Fawn-rearing habitat may include the area used for fawning but is usually larger and more diverse (fig. 12). Optimum rearing habitat contains a diversity of plant communities and structural conditions in close proximity and assures that fawns maintain adequate growth rates as they depend more on forage and less on milk. Plant communities that satisfy hiding and thermal cover requirements are generally used from mid-morning until late afternoon. These characteristically contain a tree overstory with at least 50-percent canopy closure, and shrub or riparian communities more than 0.6 meters (2 ft) high with canopy closures of more than 23 percent. Shrub sites used during rearing are usually located within 100 meters (330 ft) of trees. Stands that do not provide thermal or hiding cover are infrequently used during the day; and are generally used for forage during morning and evening (Sheehy 1978). In most rangeland the need for thermal and hiding cover is greater than the supply.

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[3] Nellis, C. Unpublished data on file at Idaho Fish and Game Department, Jerome, Idaho.

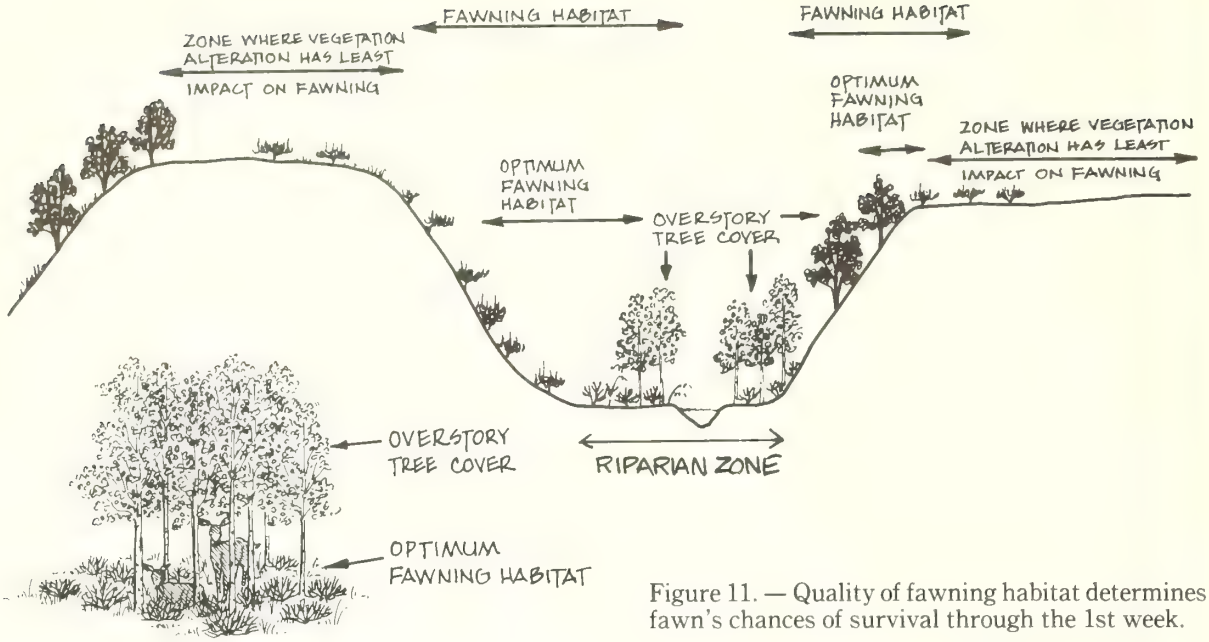

Figure 11. — Quality of fawning habitat determines a fawn's chances of survival through the 1st week.

Sheehy (1978) found that during the rearing period, fawns usually stayed within 1 kilometer (0.6 mi) of the fawning site. In the 1st month of life, movement averaged 0.6 kilometer (0.4 mi); thereafter single fawns moved less (0.5 kilometer or 0.3 mi) than twins, who moved 0.8 kilometer (0.5 mi). The optimum size for fawn-rearing areas appears to be about 160 hectares (395 acres). On Steens Mountain, in Harney County, Oregon, 90 percent of the fawn-rearing areas observed were this size or smaller; they ranged from 16 to 367 hectares (39 to 907 acres); the median was 81 hectares (200 acres). Twin fawns tended to occupy larger rearing areas than single fawns.

Fawn-rearing areas should not be regarded as independent units because there is considerable overlap in use of areas. It is important to identify and manage generalized fawn-rearing habitat rather than focusing on individual rearing areas.

Rehabilitation of fawning habitat may be desirable where stands appear decadent. Since control of shrubs replaces cover areas with forage areas, herd requirements and the probable impacts of reducing cover should be evaluated prior to treatment.

### Proportion of Cover to Forage

We suggest that optimum mule deer range should contain a mixture of plant communities and structural conditions that provide areas of optimum size and spacing that add up to at least 55 percent forage areas, 20 percent hiding cover, 10 percent thermal cover, 10 percent fawn-rearing habitat, and 5 percent fawning habitat (fig. 13). On winter ranges where the option is available, thermal cover should be emphasized in place of habitat for fawning and fawn-rearing and up to 20 percent of the hiding cover, because thermal cover usually also provides hiding cover. A greater shift is not desirable because hiding cover contributes more to winter browse than thermal cover.

Success in managing habitat for mule deer should be measured in part by herd productivity. Goals for producing animals that survive in good condition and produce the desired number of fawns can be used to measure the success of habitat management in satisfying cover and forage requirements. Based on data adapted from another study (Leckenby 1978c, Leckenby and Adams 1978) an index of productive survival (PS) was estimated for four subpopulations of a herd near Silver Lake, Oregon. Productivity was estimated from a ratio of the maximum count of deer for each subpopulation to the population of the entire herd. Survival for each unit was estimated from the proportionate decline from fall to spring in the number of fawns per adult.

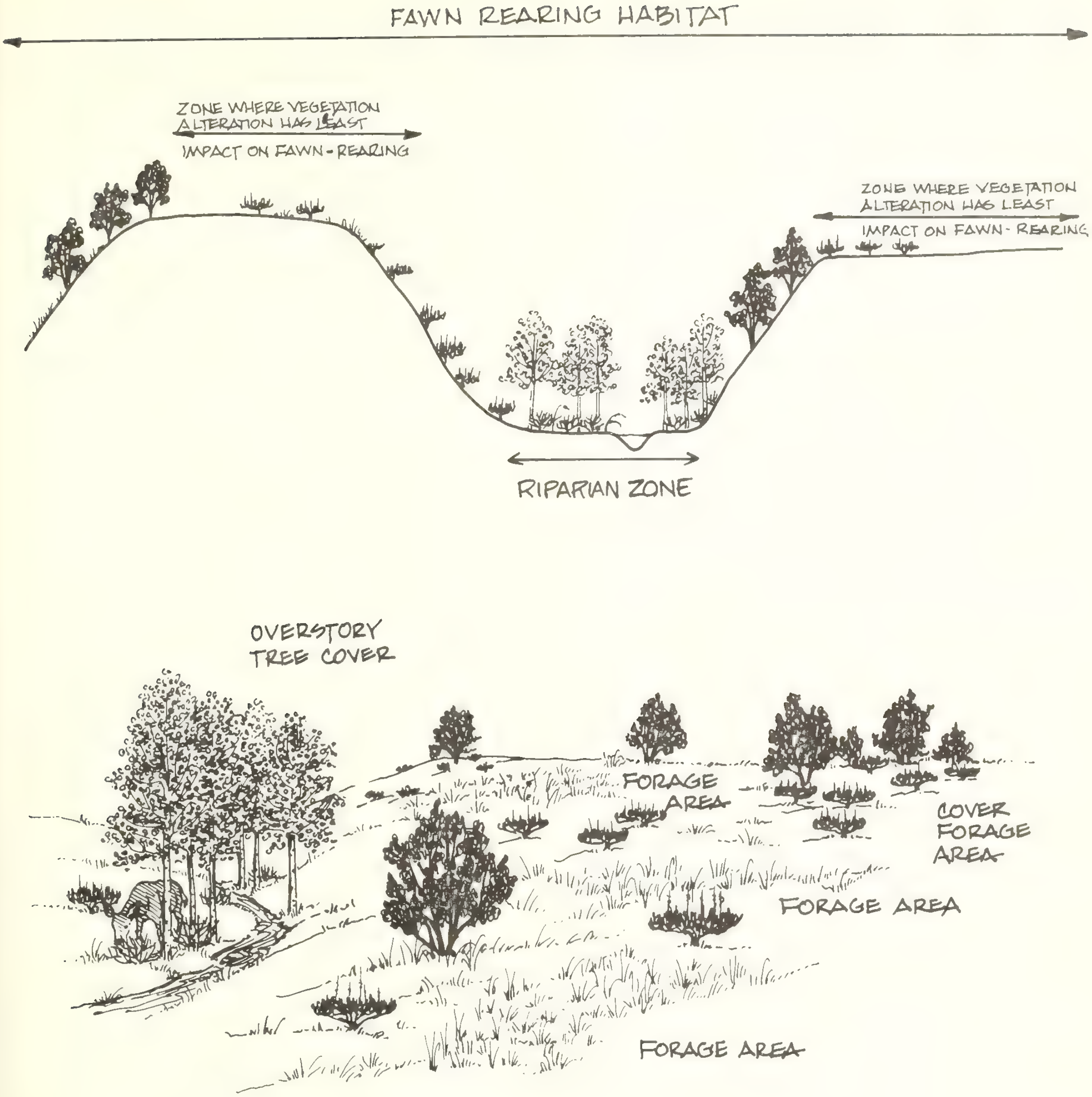
FAWN REARING HABITAT
ZONE WHERE VEGETATION ALTERATION HAS LEAST IMPACT ON FAWN-REARING
ZONE WHERE VEGETATION ALTERATION HAS LEAST IMPACT ON FAWN-REARING
RIPARIAN ZONE
OVERSTORY TREE COVER
FORAGE AREA
COVER FORAGE AREA
FORAGE AREA
FORAGE AREA

Figure 12. — Quality of fawn-rearing habitat determines the growth rate and survival of fawns through the 1st year.

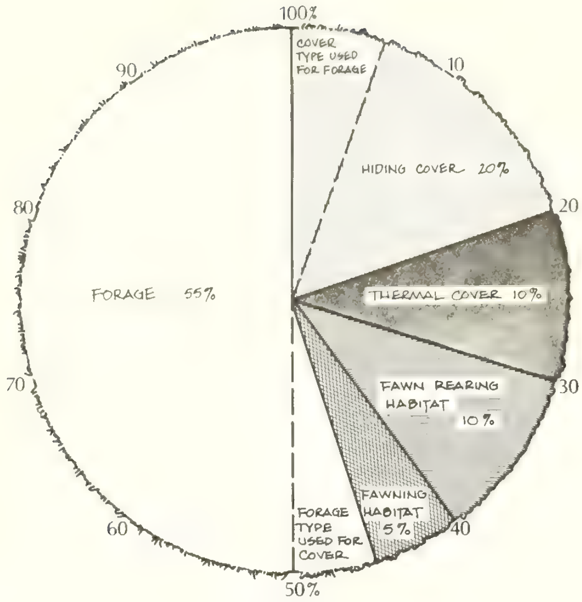

Figure 13. — Optimum mix of cover and forage for deer on shrub-steppe rangeland. Where there is a choice, thermal cover should be increased.

Calculation for each sample unit was as follows:

$$PS_i = (100)\ \frac{(d/ha/t)i}{\sum_{i=1}^{n} d/ha/t}$$

$$+\ (100)\ \frac{1.0 - (f\text{-}s/f)i}{\sum_{i=1}^{n} 1.0 - (f\text{-}s/f)}$$

where: d is the maximum count of deer
ha is the area of a unit in hectares
t is the number of counting periods
f is the count of fawns per count of adults in fall times 100
s is the count of fawns per count of adults in spring times 100
i is a sample unit of the herd range

Comparison among the four subpopulation ranges, based on new analyses of data (Leckenby 1978c, Leckenby and Adams 1978) on the number of deer, amount of plant community use, number of fawns, and severity of weather suggest that maximum productive survival was attained where cover areas comprised about 45 percent of a subpopulation range (fig. 14). Ratios of cover to forage were computed independently from plant communities within each management unit.

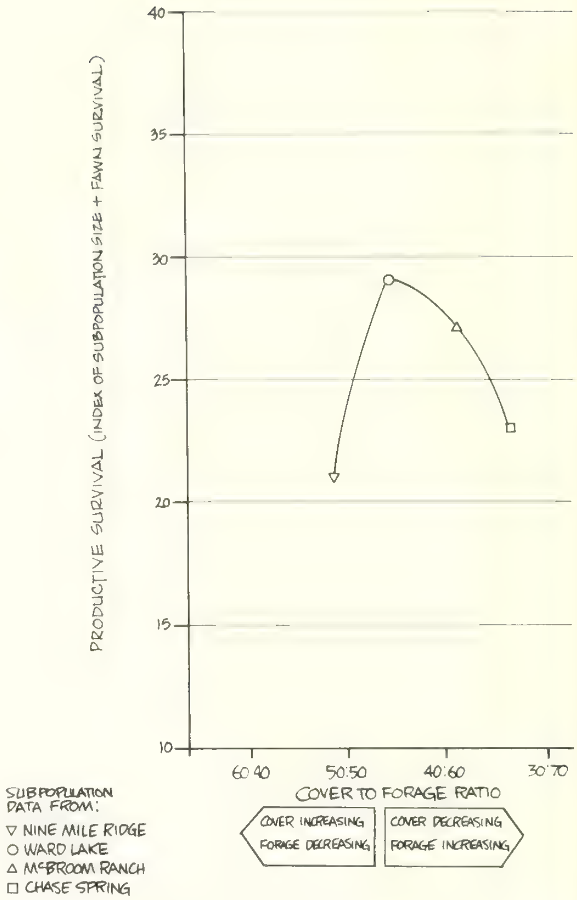

Figure 14. — Productive survival appeared maximum when cover areas made up 45 percent of mule deer winter range and forage areas made up 55 percent (adapted from Leckenby 1978c, Leckenby and Adams 1978).

Management actions that might shift the ratio of cover to forage should be based on both the total area that is currently occupied by each plant community and the area that may reasonably be expected to produce cover or forage within the usual treatment period.

A ratio of 40 percent cover to 60 percent forage appears to be consistent with proportions observed, estimated, or recommended by several authors who have studied deer herd ranges (Leopold et al. 1951:23, 129; Reynolds 1969a, 1972; Taber and Dasmann 1958:55; Terrel 1973; Thomas et al. 1979).

### Riparian Zones

Because rangelands tend to be arid, streamsides, spring areas, and moist sites are important for mule deer. Riparian zones contain the only permanent or seasonal water and often enclose the most vegetationally productive sites found over long distances. They provide a diversity of plant species that usually offer good thermal and hiding cover and prolong the availability of succulent forage. They are especially important during fawn-rearing because supplies of basic needs are concentrated in them. The intense competition for cover, food, and water in riparian zones attests to their value (fig. 15), and unregulated use by livestock and people often reduces the availability of these resources to deer (Johnson and McCormick 1978, Owen 1980). Sheehy found that riparian vegetation was contained within every home range of fawns he observed.[4]

### Water Sources

Although some studies suggest that deer require potable water for maximum production, others show that deer survive in regions where water sources are either far apart or seasonally intermittent (Dasmann 1971, Elder 1956). Numbers of deer fluctuate more in marginal habitat than on optimum ranges. We consider ranges less than optimum where water sources are farther than 320 meters (1,050 ft) apart.

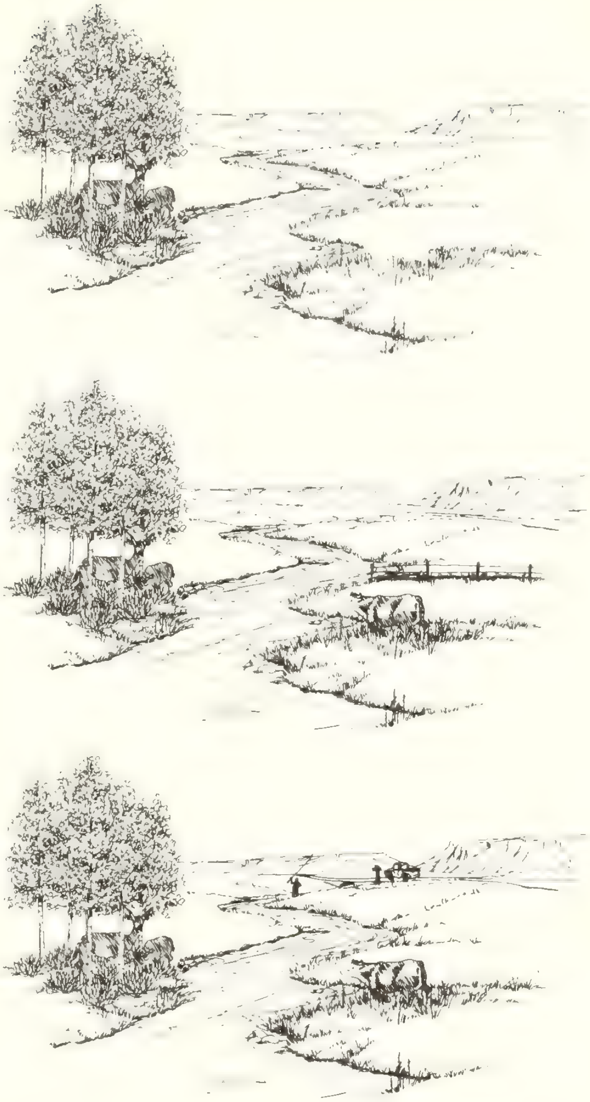

Figure 15. — Planning for riparian zones is singularly important. In them deer face increasing disturbance and competition from livestock and people.

Energy expended for travel to water reduces the amount available for survival or production. For example, a 68-kilogram (150-lb) doe would expend about the same amount of energy to walk 1 kilometer (0.6 mi) on level ground as she would use to produce 22 grams (0.7 oz) of milk or to raise a liter of water from 0°C (32°F) to her body temperature of 39°C (102°F). But she would use three times the amount of energy needed to walk that distance if water was not available and she consumed the equivalent as snow. These comparisons are calculated from estimates of the energy costs of walking on the level, producing milk, melting snow and heating water (Lange and Forker 1961:1539, 1549; Moen 1973:349, 354-356).

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[4] Sheehy, D.P. Personal communication. Information on file at Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

Various techniques for improving water sources or creating new ones have been developed to enhance habitat use and improve distribution and production of animals (Dasmann 1971, Yoakum and Dasmann 1969).

## Management of Great Basin Plant Communities for Mule Deer

In this report, we have placed 28 plant communities of the Great Basin of southeastern Oregon in nine management groups, compared the characteristics of each with cover and forage requirements of mule deer, and contrasted unmanaged conditions with those induced by management practices. Dealy and others (1981) described the structural and floristic detail of the 28 plant communities. We identify communities by the species that dominate or characterize them (table 1). This method is used to save space; it does not indicate the importance of the identifying species to deer. Ecological requirements of each species present in a community provide information relevant to management of the site.

Where data from southeastern Oregon were lacking, we reviewed published information on the interactions of deer with cover and forage in similar plant communities for indications of relationships.

### BIG SAGEBRUSHES

Although the various forms of big sagebrush (Beetle 1960, Hanks et al. 1973, Winward 1980, Winward and Tisdale 1977) differ in importance to mule deer, all are used for cover, forage, or both (Leckenby 1968, 1978c; Owen 1980; Sheehy 1975, 1978; Tueller and Monroe 1975).

#### Deer Use

The evergreen nature of big sagebrushes sustains their cover value throughout the year. Basin big sagebrush offers thermal and hiding cover because of its height, upright growth, and relatively dense crown. A tree-like form is often the result of livestock grazing. Mountain big sagebrush also forms good thermal and hiding cover because it usually has a dense canopy both vertically and horizontally, although it has a table-like form and does not grow as tall as basin big sagebrush. The close association of foothill big sagebrush with western juniper makes it somewhat less important as cover, although it can resemble the mountain form. Stands of Wyoming big sagebrush and alpine big sagebrush usually do not offer good hiding or thermal cover because of low height, low density, and open distribution.

Deer do not browse big sagebrush forms equally. Sheehy (1975) ranked their palatability as follows: foothill big sagebrush, good; mountain big sagebrush, good to fair; Wyoming big sagebrush, fair; alpine big sagebrush, poor; and basin big sagebrush, poor. Big sagebrushes generally receive greatest use in winter, moderate use in fall and spring, and lightest use in summer (Kufeld et al. 1973). Big sagebrush is more digestible when eaten in mixed diets than alone; but deer lose weight under winter weather conditions when fed only big sagebrush (Bissell et al. 1955, Dietz et al. 1962, Smith 1950). Yet, because they are evergreen, big sagebrushes are often the best available forage. Many plants associated with big sagebrushes are important deer forage (Kufeld et al. 1973).

Because of its form, palatability, and distribution, mountain big sagebrush offers optimum habitat for fawning and fawn-rearing within the shrub-steppe region (Sheehy 1978). The other big sagebrushes are used when they provide the best habitat available, but they are generally inferior to mountain big sagebrush.

#### Response to Management

Plans to manipulate big sagebrush stands to benefit mule deer must specify the plant community, the subspecies of sagebrush, the method of treatment, the size and arrangement of existing stands and proposed treatments, and the livestock grazing system.

Reducing big sagebrush cover can benefit deer in the following situations: (1) homogeneous blocks of big sagebrush wider than 380 meters (1,250 ft) which lack diversity within the grass-forb layer; (2) seasonal range where green forage is insufficient but cover is excess, such as at lower elevations where favorable exposure permits early greenup; (3) where big sagebrush is less desirable than meadow and riparian plant communities. Deer productivity can increase following reduction of big sagebrush, provided diversity, size of treatments, and cover-to-forage ratios are near optimum.

## Table 1 — Habitat values and importance of plant communities for deer

| Plant community and key plant | Elevation | Habitat value | Range | Importance[1] |
|---|---|---|---|---|
| **Tall sagebrushes:** | | | | |
| Mountain big sagebrush | Above 3,500 ft (common) | Hiding and thermal cover (good), forage (fair), fawning (good), fawn-rearing (good) | Summer, winter, and spring-fall | 1 |
| Foothill big sagebrush[2] | Below 5,000 ft (limited) | Hiding and thermal cover (good), forage (good), fawning (fair) | Spring-fall | 2 |
| Alpine big sagebrush | Above 3,500 ft (limited) | Hiding and thermal cover (poor), forage (poor) | Summer | 2 |
| Wyoming big sagebrush | Below 6,500 ft (common) | Hiding and thermal cover (poor), forage (fair) | Winter | 1 |
| Basin big sagebrush | Below 7,000 ft (common) | Hiding and thermal cover (good), forage (poor) | Winter | 1 |
| Silver sagebrush | Above 4,000 ft (limited) | Hiding and thermal cover (fair or poor), forage (good) | Summer and winter | 2 |
| **Short sagebrushes:** | | | | |
| Low sagebrush | Below 9,000 ft (common) | Hiding and thermal cover (poor), forage (good) | Summer, winter, and spring-fall | 1 |
| Stiff sagebrush | Below 7,000 ft (limited) | Hiding and thermal cover (poor), forage (fair) | Summer, winter, and spring-fall | 2 |
| Black sagebrush | Below 9,000 ft (limited) | Hiding and thermal cover (poor), forage (poor) | Summer and winter | 3 |
| Early low sagebrush | 6,000 - 8,000 ft (limited) | Hiding and thermal cover (poor), forage (poor) | Spring-fall | 3 |
| **Other shrubs:** | | | | |
| Bitterbrush | 4,000 - 7,000 ft (common) | Hiding and thermal cover (good), forage (good) | Summer, winter, and spring-fall | 1 |
| Greasewood | Below 5,000 ft (common) | Hiding and thermal cover (poor), forage (poor) | Winter | 3 |

Table 1 — Habitat values and importance of plant communities for deer, continued

| Plant community and key plant | Elevation | Habitat value | Range | Importance[1] |
|---|---|---|---|---|
| Shadscale | Below 5,000 ft (limited) | Hiding and thermal cover (poor), forage (fair) | Winter | 3 |
| Snowberry | 5,000 - 8,000 ft (limited) | Hiding and thermal cover (good), forage (good), fawning (good), fawn-rearing (good) | Summer and spring-fall | 1 |
| Snowbrush | Above 5,000 ft (limited) | Hiding and thermal cover (good), forage (good), fawning (good), fawn-rearing (good) | Summer | 1 |
| Chokecherry; bitter cherry | 4,000 - 7,000 ft (limited) | Hiding and thermal cover (good), forage (good), fawn-rearing (good) | Summer | 1 |
| Willow | All elevations (common in riparian habitat) | Hiding and thermal cover (good), forage (good), fawn-rearing (good) | Summer | 1 |
| Squawapple | 2,500 - 6,000 ft (limited) | Hiding and thermal cover (fair), forage (fair or poor) | Spring-fall and winter | 2 |
| **Trees:** | | | | |
| Quaking aspen | 5,000 - 9,000 ft (common in moist sites) | Hiding and thermal cover (good), forage (good), fawning (good), fawn-rearing (good) | Summer and spring-fall | 1 |
| Mountain-mahogany | 5,000 - 7,000 ft (limited) | Thermal cover (good), forage (fair) | Summer and spring-fall | 1 |
| Mountain-mahogany/shrub | 5,000 - 7,000 ft (limited) | Hiding and thermal cover (good), forage (good), fawn-rearing (fair) | Summer and spring-fall | 1 |
| Western juniper | Below 6,000 ft (common) | Hiding and thermal cover (good), forage (fair), fawn-rearing (fair) | Summer, winter, and spring-fall | 1 |
| Western juniper/shrub | Below 6,000 ft (common) | Hiding and thermal cover (good), forage (good), fawning (fair), fawn-rearing (fair) | Summer, winter, and spring-fall | 1 |

## Table 1 — Habitat values and importance of plant communities for deer, continued

| Plant community and key plant | Elevation | Habitat value | Range | Importance[1] |
|---|---|---|---|---|
| Cottonwood | 2,500 - 4,000 ft (limited riparian) | Hiding and thermal cover (good), forage (good), fawning (good), fawn-rearing (good) | Summer | 1 |
| **Special communities:** | | | | |
| Riparian | All (limited) | Hiding and thermal cover (good), forage (good), fawning (good), fawn-rearing (good) | Summer, winter, and spring-fall | 1 |
| Grassland | All (common) | Forage (good, especially fall and spring greenup) | Summer, winter, and spring-fall | 1<br>2 |
| Bluebunch wheatgrass | All (common) | Forage (good, needs livestock grazing to maximize availability of new growth) | Spring, some fall, and winter | 2 |
| Idaho fescue | All (common) | Forage (good, needs livestock grazing to maximize availability of new growth) | Spring, some fall, and winter | 2 |
| Cheatgrass | All (common) | Forage (good) | Spring, fall, and winter | 1 |
| Crested wheatgrass | All (in treatment areas) | Forage (good, needs livestock grazing to maximize availability of new growth) | Spring, fall, and winter | 1 |
| Sandberg bluegrass | All (common) | Forage (good) | Spring, fall and winter | 1 |
| Bottlebrush squirreltail | All (common) | Forage (good, needs livestock grazing to maximize availability of new growth) | Spring, fall, and winter | 2 |

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[1] Importance to deer, based on habitat value and distribution: 1 high, 2 moderate, 3 least.

[2] Unrecognized variant of big sagebrush (Sheehy 1975).

Conversely, reducing the cover reduces deer productivity in the following situations: (1) where fawning and fawn-rearing habitat is limited; (2) on winter ranges with limited cover; (3) where big sagebrush provides the only cover, for example, big sagebrush islands or draws within expanses of scabland sageflats and big sagebrush around rimrocks in open desert; and (4) where riparian vegetation is not desirable or cannot be developed and big sagebrush provides a needed buffer zone of cover around springs and seeps.

Deer productivity can improve where big sagebrush cover is increased. Planting or management to favor its increase should be considered where there is a documented need; for example, creating islands of big sagebrush in vast areas of crested wheatgrass, or reestablishing a shrub layer in some juniper plant communities.

On many big sagebrush sites, herbaceous forage for deer can be increased by appropriate livestock grazing and by reducing shrub density and planting grasses and forbs (Koehler 1975, Plummer et al. 1968, Roberts 1975, Winward 1980). Cattle will eat standing dead grass. The subsequent regrowth of the shorter nutritious young leaves will then be more available to deer (Leckenby 1968, Willms et al. 1980). But when deer and livestock occupy seasonal ranges simultaneously they compete for forage. Deer select the new growth of grass, forb, and shrub species that are also eaten by cattle, sheep, horses, and goats. Separating livestock from deer by season of grazing or by fences is the key to reducing direct competition. Plant vigor is best maintained by grazing livestock during periods of plant dormancy. The next best management for plant vigor is to alternate short, intense grazing periods with periods of nonuse that coincide with soil moisture levels which allow regrowth and recharge of plant nutrients. Intensity of livestock grazing is important, but so is the season, duration, and frequency. The relative impact of these four grazing variables depends on how a grazing system interacts with the plant community (Hanley 1979). Livestock grazing can create tree-like cover in basin big sagebrush, but the cover value of other big sagebrush communities is reduced when their forage value is increased. Although observations indicate that mountain big sagebrush does not survive severe browsing as well as bitterbrush or mountain-mahogany, "hedging" effects of browsing by cattle on most shrub species may create a crown that is better protected from overuse by deer. In decadent stands of mountain big sagebrush, cattle grazing appears to stimulate plant reproduction by clearing away dead debris which retards seedling establishment.

## SCABLAND SAGEBRUSHES

Several short sagebrush species (low sagebrush, early low sagebrush, black sagebrush, and stiff sagebrush) occupy harsh, rocky, shallow-soil scablands throughout the range of mule deer (Beetle 1960). These small sagebrushes provide little cover but offer forage of varying importance to deer (Leckenby 1968, 1978c; Sheehy 1978; Tueller and Monroe 1975).

### Deer Use

Because of their small stature, short sagebrushes offer little thermal or hiding cover. Deer feed in the exposed habitats of short sagebrush scablands, principally during the mild weather of sunny, calm days in winter and near sunrise and sunset in summer.

The short sagebrushes are closely browsed throughout their distribution. In trials with deer and sheep, Sheehy (1975) ranked preference for low sagebrush as fair and black sagebrush as poor. Preference for stiff sagebrush is probably fair and may be seasonal because it is deciduous. Preference for early low sagebrush is probably fair and use may be influenced by its very early flowering and seed ripening (see footnote 4). Black sagebrush appeared to be slightly more digestible than big sagebrush, perhaps because of its small stems and leaves (Smith 1950). Sheehy (1975) measured digestibility of low sagebrush at 44.3 percent. Kufeld and others (1973) reported moderate use in fall, winter, and spring. Use throughout the year has been observed (Leckenby 1969).

In spring and early summer the forbs and grasses associated with short-sagebrush communities are important to deer. New growth is early and abundant in these scablands because the shallow, rocky soils warm quickly, especially on southerly aspects. Phenological development influences the timing of use by deer. Sandberg bluegrass, crested wheatgrass, and starved milkvetch are used very early, but migratory deer seldom have an oportunity to feed on bluebunch wheatgrass and curvepod milkvetch because these plants normally initiate growth too late in the season. The immature stages of bluebunch wheatgrass, western needlegrass, and similar species are of value to nonmigratory deer, however, because their slower development provides digestible forage later in summer.

Although short sagebrush stands do not provide the cover essential for hiding and protecting fawns from predators and the elements, they are desirable in fawning and fawn-rearing areas since they often have abundant forbs and water during the early fawn-rearing period.

### Response to Management

Present range treatment methods offer little potential for improving the cover value of scabland sites to mule deer. It is not practical to increase cover, although more cover would be beneficial. The sites are too harsh to support tall plants which could improve cover, and techniques for establishing them are not available.

Methods have not yet been developed for increasing deer forage on many short-sagebrush scablands (Winward 1980), but forb, grass, and browse composition of some stands has been improved by manipulation with fire, machinery, and chemicals. The shrubs can be eliminated and grasses emphasized by flooding, the management practice termed "water spreading," but this treatment decreases winter forage.

In stands of low sagebrush that appear to be dying because of competition with rank bunchgrass, livestock grazing could make the young growth of the grasses available to deer. Grazing would also tend to promote growth of low sagebrush browse.

Spring and early summer are times when livestock management can effectively modify forage production, but also times when competition between livestock and deer for forage is maximum. Periodic rest from grazing has to be adjusted to the early initiation of growth and late seed maturity of forbs in low sagebrush communities.

## SILVER SAGEBRUSHES

Silver sagebrush communities are unique habitats that contribute to diversity and increase edge in areas dominated by tall sagebrush, short sagebrush, juniper, and pine communities. They are closely associated with drainage ways and basins. Beetle (1960) recognized at least two subspecies: a Bolander form that occurs in closed desert basins and a mountain form associated with riparian habitats. Leckenby (1978c) found that deer preferred Bolander silver sagebrush communities on winter range. Dealy (1971) considered mountain silver sagebrush communities of low value to deer on summer range.

### Deer Use

The medium stature of silver sagebrush provides some hiding cover for mule deer, but plant density and canopy cover are usually low and offer little protection from weather.

Deer browse silver sagebrushes in fall, winter, and spring[5] (Kufeld et al. 1973). In browsing trials with captive mule deer, Sheehy (1975) found that Bolander silver sagebrush was one of the most preferred.

Site, phenology, and the availability and diversity of forage plants influence the degree and season of deer use of silver sagebrush basins. Lengthy spring flooding—normally up to a month—is characteristic of these communities and encourages lush growth of native forbs and grasses adapted to flooding. Associated forage plants that deer apparently prefer to sagebrush when they are available are muhly, Newberry's cinquefoil, Fremont combleaf, and other grasses and forbs in early growth stages. These are more nutritious than the older silver sagebrush browse.

Riparian zones dominated by mountain silver sagebrush communities provide fair cover and forage near water during much of the fawn-rearing period and are sufficiently valuable to mule deer to warrant protection. Persistent spring flooding, however, makes Bolander silver sagebrush communities unsuitable; after they dry, the flats are of little value for fawn-rearing because hiding cover, thermal cover, and forage are inadequate.

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[5] Leckenby, D.A. Unpublished data on file, Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

### Response to Management

Current techniques for manipulating habitat cannot increase the cover value of silver sagebrush communities and will decrease the little value they possess. The extremes of flooding and drying each year eliminate introduced shrubs which might otherwise provide increased cover.

Reducing cover, with or without soil disturbance, does increase forb and grass forage. Leckenby (1969) found that unusually long ponding significantly reduced Bolander silver sagebrush cover in closed basins in south-central Oregon for several years. This was followed by an increase in Newberry's cinquefoil and desert combleaf forage which was significant in the diet of mule deer through a mild winter. Most of the grasses and forbs planted to produce forage in range communities will not survive the inevitable spring flooding and summer drying in Bolander silver sagebrush stands (Leckenby and Toweill 1979a, Winward 1980).

Water holes and drainage ditches that are frequently dug in silver sagebrush basins quickly concentrate runoff water into deeper reservoirs. These retain water much longer than the wide, shallow ponds that collect water naturally and allow it to evaporate rapidly. Created water holes have an obvious positive benefit for wildlife and livestock, but they also have adverse impacts on wildlife. Some drain the basin so efficiently that big sagebrush and rabbitbrush are able to invade and replace the silver sagebrush.

Other methods have provided valuable water reservoirs without sacrificing the unique qualities of silver sagebrush communities. For example, "guzzlers" (catchment aprons with storage tanks) have been installed in adjacent expanses of tall and short sagebrush or western juniper.

Livestock grazing of mountain silver sagebrush stands can benefit mule deer by removing cured grass from summer range; however, this must be managed to protect plant vigor and prevent damage to the riparian zone. Competition between deer and livestock for forage is likely to occur in these riparian communities on summer range (Dealy 1971, Dusek 1975). We found that summer cattle grazing of silver sagebrush basins on deer winter range resulted in minimal competition but may have reduced plant vigor. Trampling of the associated moist clay soils in late spring and early summer compacted the soil and altered plant composition (Leckenby 1978c).

## ANTELOPE BITTERBRUSH

Although it forms pure stands elsewhere (Daubenmire 1970, Nord 1965), antelope bitterbrush is usually one of several shrub species found in browse stands in the Great Basin. Managers have historically considered this species one of the most important deer browse plants in the West. Its stature, crown, form, and abundant fruit offer both obvious and subtle benefits for many species of wildlife. Its structural and foliage attributes greatly influence microclimate and provide cover and forage values associated with high levels of use by both deer and livestock (Hormay 1943, Leckenby 1978c, Tueller and Monroe 1975).

### Deer Use

On many winter ranges, antelope bitterbrush provides exceptionally good hiding cover in both big and short sagebrush stands. Although deciduous, bitterbrush contributes to thermal cover on winter range because it is taller and has larger crowns than the sagebrushes, but it is not tall or dense enough to make good thermal or hiding cover under overstories of western juniper, ponderosa pine, and lodgepole pine on summer ranges.

Antelope bitterbrush is eaten by deer in all seasons, but major use occurs in late summer, fall, and early winter (Kufeld et al. 1973, Leach 1956, Leckenby 1969). Weather, seasonal moisture, and availability of other foods greatly affect browsing. Secondary peaks in use are noted during dry springs; following cool, moist summers major use may not begin until fall. Hormay (1943:3, 7) found that bitterbrush produces flowers and seed only on the previous year's wood and not on the current shoots. He also concluded that at least 40 percent of each year's current leader should remain following grazing. Adams (1975) and Hormay (1943) both suspected that declines in bitterbrush populations in Oregon and California had resulted from insufficient seed production caused by severe browsing.

Others have found that bitterbrush alone is not digestible enough to provide sufficient energy for maintenance under winter stress. For example, Dietz and others (1962) and Bissell and others (1955) found that deer fed bitterbrush alone or in combination with other browse species lost weight. Deer usually seek foods more digestible and richer in energy than bitterbrush, such as young grasses and forbs, even when unused leaders of bitterbrush are abundant. When better forage is not available, however, deer browse bitterbrush severely, even clipping off 0.6-centimeter (¼-inch) diameter branchlets 2 to 4 years old[6] (Hormay 1943).

Because of their unusual density, height, and canopy closure, stands of antelope bitterbrush can provide good fawn-hiding cover; however, the usual ecological situation in which bitterbrush occurs (Nord 1965) does not assure fawn-rearing success because distances to water are usually too great, forbs and grasses mature rapidly, and temperatures are frequently extreme.

### Response to Management

In most areas where bitterbrush forms a large part of communities important to deer, reducing cover has adverse impacts on deer productivity. On the other hand, where decadent shrubs are not producing as much forage as wildlife and livestock need, replacing older canopies with young-shrub crowns is beneficial. This requires either new plants or rejuvenation of old shrubs (Koehler 1975, Plummer et al. 1968). Grass and forb production can be increased without reducing bitterbrush cover by phenologically scheduled spraying of herbicides to control sagebrush and release the herbaceous layer.

Livestock grazing in bitterbrush stands in spring and early summer before soil moisture is depleted will benefit deer in fall and winter; livestock grazing in other seasons will cause direct competition with deer for forage and reduce plant vigor and reproduction; continuous grazing in summer and fall will magnify stress on plants. Unwise grazing management results in conditions which gradually alter the value of bitterbrush communities for wildlife and livestock as well.

To produce sufficient seed to continue bitterbrush stands, Hormay (1943:7) suggested that cattle be allowed to graze shrubs and shape them into more compact form that will protect shrubs from overuse and allow 15 to 20 percent of the new shoots to escape future browsing. He recommended one season of rest from cattle browsing every 4 or 5 years. Where bitterbrush is dying and not being replaced, we concluded that 2 years of rest would be needed to maximize seed production and perpetuate threatened stands. Hormay also found that height growth was restricted by cattle browsing, which prevented the shrubs from growing out of the reach of deer.

Cattle grazing can also be used to reduce competition of forbs and grasses for water and nutrients (Smith and Doell 1968, Tueller and Tower 1979). Livestock grazing in bitterbrush stands makes more forage available to deer by removing the cured foliage so deer can reach new leaves of grass. As a result deer rely less on bitterbrush for forage.

## WESTERN JUNIPER AND JUNIPER/SAGEBRUSH

The pygmy forests — juniper woodlands of south-central and southeastern Oregon — are important to mule deer and other wildlife. They form habitats for deer which are analogous to the pinyon-juniper woodlands found elsewhere in the Great Basin and the Rocky Mountains (Holmgren 1972). During winter stress, western juniper communities were used more than any other type (Leckenby 1978a, Leckenby and Adams 1978). This woodland type comprises many communities. Juniper stands tend to be either predominantly young (40 to 80 years) or old (200 to 500 years) (Adams 1975). The structural components which juniper communities add to habitat diversity are apparently important to all aspects of deer use and range management on such sites (Leckenby and Toweill 1979a, 1979b; Reynolds 1972; Short et al. 1977; Tueller and Monroe 1975).

### Deer Use

Western juniper stands provide excellent hiding and thermal cover for wildlife because they are short, dense-canopied, and evergreen. The arrangement and mixture of juniper in shrubland and grassland communities, however, is often less than optimum, a factor which probably contributes to the loss of some deer to weather stress and starvation, no matter how mild the winter. Better distribution of cover may be the reason some deer survive even the severest winters. Leckenby (1978c) found that in winter deer used juniper for thermal cover more than they used grassland forage areas or shrubland cover-forage areas. They also used juniper intensively for thermal cover on spring and fall ranges. Spalinger (1980) found they used juniper cover for bedding in Nevada.

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[6] Leckenby, D.A. Unpublished data on file at Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

Weather stress was 40 percent less under a young juniper stand with a 25-percent canopy closure than where canopy closure was 5 percent or less (Leckenby 1978a, Leckenby and Adams 1978). Young juniper stands generally make better hiding cover than thermal cover. They also provide more grass, forb, and shrub forage than older stands. As juniper stands age and develop larger crowns and greater canopy closure and crown depth, thermal cover is improved.

Deer use juniper in all seasons, particularly during stress caused by weather and food shortages. They will browse other forage if they have the chance, probably because juniper is not digestible enough to meet their energy needs during weather stress. Although chemical analysis of Utah juniper was similar to sagebrush (Smith 1952), it was less preferred than bitterbrush or mountain-mahogany. Juniper browse probably does not provide a maintenance diet but rather a survival diet.

Old juniper stands occupy harsh sites, and current management policies prevent development or renewal of other forage within such stands. Although forage plants do grow under juniper, they cannot sustain the same intensity and frequency of cropping by ungulates they do in other settings. Native forage plants grow better than most exotics, but seeds are not commercially available (Leckenby and Toweill 1979a, 1979b).

Western juniper can hide fawns, but the aridity of stands and their lack of succulent forage through the nursing period limit their value as fawn-rearing habitat. Their usefulness depends on forage in adjacent plant communities and availability of nearby water. Patches of juniper may be used for fawning and fawn-rearing as Sheehy (1978) found aspen patches were used within expanses of sagebrush.

### Response to Management

Where juniper forms extensive, nearly monotonous stands of woodland various treatments can increase forage, edge, and diversity. Revegetation projects on sloping ranges should be restricted to corridors about 1 kilometer (0.6 mi) wide which lay across elevational contours. Projects on more level ranges should radiate from fawn-rearing areas and riparian zones. Habitat quality, defined by optimum sizes and distribution of cover and forage areas, edge distances, and diversity can be improved by appropriate cutting, chaining, and burning of units distributed within a larger project area. Such planning of treatment projects within management units is most compatible with ranges of deer subpopulations (Leckenby 1977, 1978a, 1978b).

Weather stress in the Great Basin makes thermal cover exceptionally important on all mule deer ranges. The vegetation influences on microclimates determine how much juniper communities can be manipulated while preserving thermal cover. Sizes of patches and distances between them must be considered.

Deer utilize forage better in smaller openings within juniper stands. Created forage areas, therefore, should be irregular, long, and no wider than 60 meters (200 ft), assuming an average juniper height of 6 meters (20 ft). Openings up to five tree heights in width allow wind speeds only 30 percent of speeds in areas where there is no cover at all (Geiger 1966). But compact openings smaller than recommended, increase turbulance in eddies which can exceed the speed of winds above the canopy (Bergen 1971, Geiger 1966, Gifford 1973). The long axis of forage openings should lie perpendicular to prevailing winds on winter ranges to minimize chilling and east-west on summer ranges for optimum shading. Temperature extremes in forage areas also vary with adjacent cover height (Bergen 1972, 1974; Cochran 1969; Geiger 1966; Moen 1968c, 1973).

The effectiveness of juniper cover depends primarily on structure and secondarily on how well stand sizes match the space required by social groups of deer. Juniper cover areas should be at least 91 meters (300 ft) wide to create adequate thermal protection and at least 183 meters (600 ft) wide to meet hiding requirements.

The latter dimension probably allows sufficient space for most social groups. Little additional effect or microclimate results when thermal cover stands are wider than three stand heights (Geiger 1966, Reifsnyder and Lull 1965). Wider stands, however, can accommodate more deer by providing enough preferred habitat to reduce conflicts between animals. Deer use increased in pinyon-juniper islands when 30 percent of treatment areas were retained in cover patches at least 152 meters (500 ft) wide, 10 hectares (25 acres) in size, and areas were no farther apart than 0.8 kilometers (0.5 mi) (Reynolds 1972).

Habitat diversity and structural qualities unique to juniper should be retained where stands comprise less than 40 percent of a management unit. Even though control techniques work better on larger junipers, it is not wise to concentrate treatment in older stands because recovery of their unique structural qualities will probably require several centuries.

The competition and seasonal availability of forage within juniper communities will indicate whether changes in livestock grazing or revegetation are necessary to provide additional forage. Manipulation of grazing intensity or season may enhance native forage by selective release. Several options are available when revegetation is selected as a way to increase forage (Koehler 1975, Plummer et al. 1968, Vallentine 1971). Planting forage species under standing juniper can increase spring forage without reducing cover (Leckenby and Toweill 1979b).

It is more difficult to attain a beneficial effect from livestock grazing in juniper stands than in most other habitats. On most sites, establishment and growth of deer forage is hindered by aridity, temperature extremes, shallow soils, and low fertility. The adverse impacts of severe grazing are prolonged by these harsh conditions. Although heavy livestock grazing in the past eliminated forage species in many stands, grazing can improve forage for deer if cattle graze coarse, mature plant parts. As always, requirements of forage plants must be satisfied before grazing is permitted. Livestock must be restricted to either those seasons when plants are dormant or when soil mositure levels will permit regrowth and recharge of plant reserves following grazing.

## MOUNTAIN-MAHOGANY AND MOUNTAIN-MAHOGANY/SAGEBRUSH

The evergreen nature of mountain-mahogany and sagebrushes, which are regular community associates, make stands of these species important year around habitat for mule deer. The value of each stand is determined by composition and structure. Observed deer use of mountain-mahogany communities was very high for short periods in spring and fall and low, but consistent, in other seasons (Leckenby 1969, 1978c). Owen (1980), in multivariate analyses, found that bedding, moving, and feeding were primarily associated with structural characteristics of mountain-mahogany and other plant communities and secondarily with compositional characteristics. Tueller and Monroe (1975) found moderate to low densities of pellet groups in mountain-mahogany communities compared to other types.

### Deer Use

Mountain-mahogany stands are generally short and canopies nearly closed. Cover values, therefore, are high throughout the year. These communities frequently grow in ecotones between timber and shrubland. Often they provide exceptional hiding and thermal cover close to forage areas, for example, where mountain-mahogany and short sagebursh communities adjoin.

Mountain-mahogany is browsed wherever it is found (Kufeld et al. 1973). The forage value of a particular stand depends primarily on community composition and condition, which reflect current and past grazing intensity. In most stands past use has been severe enough to create high browse lines, and the present forage value of mountain-mahogany communities is primarily in the associated shrubs, grasses, and forbs. The microclimate created by mahogany cover is thought to promote dense forbs and grasses (Owen 1980).

Excellent cover and usually good forage make mountain-mahogany stands potentially valuable habitat for fawning and fawn-rearing. But factors in adjacent areas, such as the availability of potable water and quality forage throughout the lactation period, determine their real value.

Patches of mountain-mahogany within expanses of shrubland may be focal points of fawning and fawn-rearing as Sheehy (1978) observed with aspen overstory.

### Response to Management

Present knowledge of mountain-mahogany germination, establishment, growth, reproduction, and sprouting is limited (Dealy 1975). Thus, results of manipulating mahogany to increase cover and forage are unpredictable and often fail to meet treatment objectives. Management can reduce mountain-mahogany cover and produce more forage, but at the cost of habitat diversity. The present lack of understanding of the intensity of use by mule deer suggests that it is not wise to manipulate cover in stands of mountain-mahogany that are narrower than 90 meters (300 ft).

Severe browsing by deer and livestock has detrimentally affected many mountain-mahogany stands. On the other hand, livestock grazing on accumulated grass and forb litter in the understory can increase forage availability for deer. Grazing should be permitted only when plants are dormant. Numerous examples show that too much grazing, grazing at the wrong time, grazing at the same time every year, as well as too little grazing can all reduce forage availability.

## SALT DESERT SHRUB: BLACK GREASEWOOD, SPINY HOPSAGE, AND SHADSCALE

Few mule deer utilize black greasewood, spiny hopsage, or shadscale communities. Although these communities provide sufficient hiding cover for bedded deer, thermal cover is poor, and most associated forage species are available for only short periods in early spring. Mule deer frequent the adjacent tall- and short-sagebrush communities much more. Where they are interspersed as small stands among expanses of sagebrush, the black greasewood, spiny hopsage, and shadscale communities improve habitat diversity and offer additional forage species, such as bud sagebrush and desert saltgrass. Salt desert shrub communities appear generally unimportant to deer management in this area.

## NON-SHRUB COMMUNITIES, GRASSLANDS IN GENERAL

Bunchgrass communities, burned areas, seedings, and cheatgrass stands are considered together as nonshrub communities. Grasslands are not usually considered cover areas, but Nellis[7] has found that giant wildrye stands are used as fawn-rearing cover in Idaho. Grasslands adjacent to cover may provide valuable forage, depending on the interactions of stand size, grazing management, and season (Holl et al. 1979; Leckenby 1978c; Reynolds 1962, 1964; Tueller and Monroe 1975; Willms et al. 1979).

The interspersion of forage types, particularly as small areas within cover types, results in maximum effective use of forage by both deer and livestock. Forage was most intensively used around the edges of large (80 hectares or 200 acres) areas that had been seeded and burned, while average use over the entire stand was 40 percent.[8] In smaller stands (8 hectares or 20 acres) in the same area, 90 percent of available forage was used.[9]

Deer use was greater in small stands grazed by cattle in previous seasons. Deer grazed 80 to 96 percent of the grass plants, primarily crested wheatgrass, and removed 40 to 65 percent of the available spring growth in pastures grazed by cattle in the previous summer, but on pastures from which cattle had been excluded by fences, deer grazed only 16 to 20 percent of the grass plants and ate only 10 to 20 percent of the available spring growth (Leckenby 1968). Similar patterns of use by deer following cattle use were observed where range treatment or wildfire had produced grass stands dominated by bottlebrush squirreltail.

Nonshrub plant communities are most valuable to mule deer during fall, spring, and summer because of the lush green growth produced by precipitation in fall and ample soil moisture in spring. Fresh immature forage is high in nutrients, digestibility, and moisture and low in fiber, regardless of plant species (Subcommittee on Feed Composition 1969). Fall greenup permits deer to add to nutrient reserves before the stresses of winter. Rich and digestible new growth may also increase ovulation rates. Spring and early summer greenup supplies quality forage at a critical time when body reserves are nearly depleted, fetuses are growing rapidly, does are lactating, and deer are migrating.

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[7] Nellis, C. Unpublished data on file at Idaho Fish and Game Department, Jerome, Idaho.

[8] Bolstad, R. Unpublished data on file at Lakeview District, Bureau of Land Management, Lakeview, Oregon.

[9] Leckenby, D.A. Unpublished data on file at Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

## SPECIAL PLANT COMMUNITIES

The Great Basin contains additional plant communities that are unique or different from the majority of habitats in the area. They are especially important to deer because they are limited in extent and because they provide valuable habitat within expanses of less hospitable habitat or satisfy deer needs during certain times of the year. They include riparian zones, pine and fir forests, and aspen, squawapple, snowbrush, snowberry, chokecherry, and bitter cherry communities. Management of these environments requires especially careful evaluation, and maintenance is often the best choice.

### Riparian

Riparian zones are especially valuable for fawn-rearing, summer and winter thermal cover, and late season forage. Willow, dogwood, cottonwood, and other characteristic riparian plant communities provide concentrations of what Leopold (1933:29) called welfare factors — cover, food, and water. Because of these factors, riparian zones are often centers of intense competition among wildlife, livestock, and people. Agricultural activities, housing subdivisions, and recreational developments reduce habitat and increase conflicts. Mule deer are subject to more frequent and more intensive disturbance in riparian communities than in any other habitat throughout the Great Basin. Any development or overuse of riparian zones reduces their value as deer habitat.

### Pine and Fir Forest

Pine and fir forest types are limited in the Great Basin and are generally restricted to relict stands in unique situations. Because seed sources are isolated, environments are harsh and exacting, successional stages are persistent, and tree growth is slow, these forests will probably not respond to management practices in the same manner recommended for other forested areas (Thomas et al. 1979). The foregoing factors make these forests ecologically much different from the pine and fir stands elsewhere — in the Blue Mountains, for example. Management proposals to manipulate or exploit these environments require careful evaluation. The precarious existence of these stands, their small size, their unique contributions to habitat diversity, and their importance to wildlife suggest that management to perpetuate and preserve them has a far sounder basis than management for timber production or livestock forage.

### Aspen

Quaking aspen communities add considerably to the beauty and diversity of the Great Basin shrub-steppe and are second only to riparian zones in importance to mule deer. They provide extremely valuable cover and forage during fawning and fawn-rearing (Sheehy 1978). They also provide patches of valuable hiding and thermal cover within expanses of sagebrush. They contain grasses, forbs, and shrubs that provide good summer and autumn forage (Smith et al. 1972). Snowberry, for example, is a common and important browse component of these stands.

Competition between mule deer and livestock for aspen habitats is high because of the excellent cover and forage they provide. Alteration of cover and severe grazing within these communities can have adverse impacts on deer. Severe browsing of aspen sprouts appears to limit regeneration of the overstory and probably results from the competition for forage and space (Smith et al. 1972). While removal of aspen is usually detrimental to the welfare of mule deer, the value of decadent stands may be improved by prescribing burning, cutting, and grazing management (DeByle 1978, Patton and Jones 1977, Reynolds 1969b, Smith et al. 1972). Aspen stands should receive special evaluation during planning.

### Squawapple

Squawapple communities provide cover and forage for mule deer. Associated grasses and forbs are particularly valuable during early spring growth. These plant communities are often semiriparian, occurring in moist swales in association with scabland vegetation types. Their value is heightened because of their association with adjacent communities that are deficient in cover. Like riparian zones, squawapple communities are focal points for competition between livestock and deer, especially in late spring. Nearby conifer stands often provide fawning habitats. The stands should be managed to enhance their cover and forage attributes while maintaining their contribution to habitat diversity of rangelands.

### Snowbrush

The stature, form, density, and evergreen nature of snowbrush make it particularly valuable to deer in all seasons. It quickly invades burns and establishes large forage areas. It is important in summer and fall diets (Leach 1956). In late summer, fall, and winter, the evergreen foliage is more nutritious than stems of many deciduous browse species. On productive sites, within 10 years after burning snowbrush will produce a canopy of adequate height and closure to provide thermal and hiding cover on summer and spring-fall ranges. On sites near intermittent or permanent water, the thermal and hiding cover provided by snowbrush communities can be excellent [10] (Sheehy 1978).

Since snowbrush quickly becomes tall and dense on good sites, optimum production and availability of understory plants lasts only a few years. Prescribed burning can perpetuate cover and forage diversity over extended periods (see footnote 10). Burning is necessary to break seed dormancy and regenerate snowbrush; mechanical and chemical treatments do not create adequate cover or forage stands as quickly as fire.

### Snowberry

Communities dominated by snowberry are neither extensive nor common in the Great Basin. Where they occur, however, they are intensively used by mule deer. They tend to be associated with specific plant habitats, such as stands of wax currant and big sagebrush on rimrocks and quaking aspen in moist locations.

Cover values of snowberry communities are generally moderate to low, although in some areas they provide excellent hiding cover. Snowberry types are used by deer as cover from spring through fall (Sheehy 1978).[11]

Snowberry is browsed the year around. Use is generally greatest in late summer and early fall but is also high in late spring at lower elevations. Spalinger (1980:123) conjectured that snowberry may be more valuable than digestion trials indicate.

Manipulation of snowberry communities in the Great Basin is detrimental to mule deer and other wildlife. This is especially true where these communities occur on rimrocks or aspen sites and provide the only diversity in uniform stands of big sagebrush.

### Chokecherry and Bitter Cherry

Stands of wild cherry species are like quaking aspen communities in many respects. They grow on moist sites in rich shrub, forb, and grass communities that often retain phenologically young forage species longer than adjacent communities and provide important mid- to late-summer habitats. These plant associations add considerable diversity to rocky rims, stream canyons, and grassland slopes in many areas. Wild cherry communities are often used intensively by livestock because they provide mild microclimates and the resulting competition with deer for space and forage is often substantial.

Chokecherry and bitter cherry, like aspen, can provide excellent thermal and hiding cover from spring through summer. Stands vary considerably in density, but spread by suckering tends to create dense irregular patches that provide cover favorable to deer.

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[10] Grogan, F. Oregon Department of Fish and Wildlife, Lakeview, Oregon. Personal communication. Information on file at Pacific Northwest Forest and Range Experiment Station, La Grande, Oregon.

[11] Nellis, C. Unpublished data on file at Idaho Fish and Game Department, Jerome, Idaho.

Although used all year, wild cherry species are browsed most intensively in fall and spring, and deer regularly consume the ripe fruit. Associated forbs also provide excellent summer forage.

Because the stands are limited and important, and since current management techniques cannot improve the cover and forage qualities of these communities, maintenance is the best management.

## Management Tips

1. Habitat management units should not exceed 4 700 hectares (11,500 acres). They should be parallel to primary drainages and ridges. On ranges with an average slope of more than 2 percent, units should be about 5 kilometers (3 mi) wide and no more than 10 kilometers (6 mi) between upper and lower elevations. On level ranges, units may approximate squares, 8 kilometers (5 mi) on all sides, or circular areas with a radius of 4 kilometers (2.5 mi).

2. Because livestock is usually the major product of managed rangelands, grazing provides the most economical tool for manipulating forage over large areas. Grazing systems can be used to manipulate vegetation and provide for all needs of deer. This requires careful planning of sizes and boundaries of pastures and rotation schedules adapted to deer subpopulation areas and seasonal movements. The usual system of rotating three or four large pastures does not allow rest periods tailored to the physiological requirements of browse species and may not leave enough forage in an intensively grazed pasture that encompasses the range of a deer subpopulation. If only lightly grazed or rested pastures encompass the range of a subpopulation, then adequate new growth of grasses will not be available. A four- to six-pasture system that includes rest and rotation may be needed to maintain or enhance preferred browse species, such as bitterbrush.

3. Riparian zones are of great importance to desert mule deer. They satisfy requirements for cover, food, water, and plant species diversity in a small space. Management of these zones requires extremely careful planning, based on comprehensive analysis of a multitude of variables (fig. 16). It is difficult to implement a livestock grazing system that will adequately protect unfenced riparian vegetation (Duff 1979, Olson and Armour 1979, Storch 1979), but management has reversed vegetation trends and deterioration on some sites (Behnke and Raleigh 1978). Reductions in stocking may not produce the desired results, since cattle tend to concentrate in riparian zones during summer and fall and use streamside vegetation intensively. Some livestock use of riparian areas may be beneficial, however, since livestock tend to break down or thin out streamside growth that becomes too thick for deer movement or browsing. Classification of riparian zones by elevation would associate zones with summer, winter, and spring-fall ranges and help managers develop grazing systems compatible with the seasonal needs of deer.

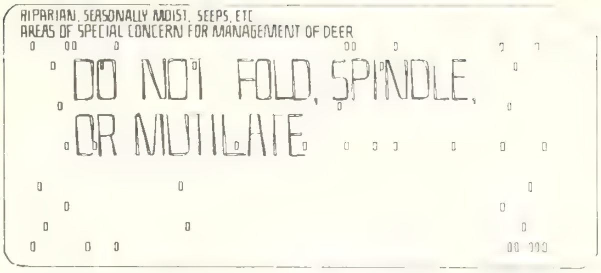
RIPARIAN, SEASONALLY MOIST, SEEPS, ETC
AREAS OF SPECIAL CONCERN FOR MANAGEMENT OF DEER
DO NOT FOLD, SPINDLE, OR MUTILATE

Figure 16. — Computer techniques are helping to store and analyze data to assist managers in understanding the importance of managing riparian zones with sensitivity appropriate to their high value as habitat for deer, livestock, and people.

4. In units where deer depend on livestock watering devices, such devices should remain in operation after the livestock grazing season. Overflow water piped from troughs into managed pastures or livestock exclosures can promote forage for deer and cover for other wildlife. The benefits from such water management must be balanced against loss of cover provided by juniper and sagebrushes, which are intolerant of soil saturation.

5. Most vegetation conversions replace cover and browse with livestock forage, chiefly exotic grasses. Such treatments can reduce deer use through loss of cover and winter forage. Grass monocultures wider than 366 meters (1,200 ft) are poor deer habitat. Removal of woody, nonforage species is not always desirable because they may provide thermal and hiding cover for deer. Good deer range requires a mixture of grass, forbs, browse, and cover species.

6. Vegetation improvement projects to benefit mule deer should be implemented only after five conditions have been met:

(a) Biological data show a need for range improvement.
(b) Moderate techniques, such as changes in livestock grazing or herd size, have not improved conditions.
(c) Plant communities have been identified.
(d) The probability of attaining project objectives on that site within a reasonable time is high.
(e) Effects on ecosystems and probable future land uses and management options have been evaluated.

7. The success of habitat rehabilitation projects should be measured by impacts on all resources, as well as costs of treatment.

8. Size of areas to be treated by plowing and seeding or other programs should be selected to produce the appropriate ratio of cover to forage, desired plant diversity, and optimum amount of edge. If range treatment includes seeding, native and adapted exotic plants should be selected to maintain a diversity of green, succulent forage over as long a time as possible.

9. Since forage productivity declines when plant requirements are not met, managers need to be as concerned with the amount of herbage left at the end of the growing season as they are with the amount consumed by deer and livestock.

10. Forage should be allocated to deer on the basis of:

(a) season of use;
(b) seasonal availability;
(c) seasonal nutrient requirements;
(d) number of deer planned for, by sex and age classes;
(e) conversion of available forage to deer unit months, a measure similar to animal unit months (AUM) but also accounting for overlap of diet and season and area of range use.

11. Management practices that encourage human use of mule deer habitat should be carefully planned so that uses are compatible.

## Conclusion

Flexibility in managing public rangelands to keep pace with society's changing demands for products is dictated by laws, such as the Forest and Rangeland Renewable Resources Planning Act of 1974 sec 2(3). As public land administrators prepare to manage all rangeland resources as intensively as they currently manage livestock, livestock management will evolve into range management, and habitat for wildlife will be maintained, increased, and enhanced. Management of range ecosystems will include refinements that account for impacts of old uses as well as new ones, as land managers decide which resources are to be emphasized and the intensity of management to be applied. Although the flow of products from most rangelands can be sustained, with more careful planning, more detailed inventories, and tighter management, we can meet the constraints of shrub-steppe ecosystems and reap additional benefits. The trick is to make management decisions that maintain harmony among natural interrelationships and human goals.

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# Appendix

## Common and Scientific Names of Plants[1]

| Name in text | Scientific name |
|---|---|
| Antelope bitterbrush | *Purshia tridentata* |
| Basin big sagebrush | *Artemisia tridentata tridentata* |
| Big sagebrush | *Artemisia tridentata* |
| Bitter cherry | *Prunus emarginata* |
| Black cottonwood | *Populus trichocarpa* |
| Black greasewood | *Sarcobatus vermiculatus* |
| Black sagebrush | *Artemisia nova* |
| Bluebunch wheatgrass | *Agropyron spicatum* |
| Bolander silver sagebrush | *Artemisia cana bolanderi* |
| Bottlebrush squirreltail | *Sitanion hystrix* |
| Bud sagebrush | *Artemisia spinescens* |
| Cheatgrass brome | *Bromus tectorum* |
| Common chokecherry | *Prunus virginiana* |
| Crested wheatgrass | *Agropyron desertorum* |
| Curvepod loco | *Astragalus curvicarpus* |
| Desert combleaf[2] | *Polyctenium fremontii* |
| Desert saltgrass | *Distichlis stricta* |
| Dogwood | *Cornus stolonifera occidentalis* |
| Early low sagebrush | *Artemisia longiloba* |
| Foothill big sagebrush[3] | *Artemisia tridentata* form *xericensis* |
| Giant wildrye | *Elymus cinereus* |
| Idaho fescue | *Festuca idahoensis* |
| Lodgepole pine | *Pinus contorta* |
| Low sagebrush | *Artemisia arbuscula arbuscula* |
| Mountain big sagebrush | *Artemisia tridentata vaseyana* |
| Mountain-mahogany | *Cercocarpus ledifolius* |
| Mountain silver sagebrush | *Artemisia cana viscidula* |
| Muhly | *Muhlenbergia richardsonis* |
| Newberry's cinquefoil[2] | *Potentilla newberryi* |
| Pinyon[4] | *Pinus edulis,* and *P. monophylla* |
| Ponderosa pine | *Pinus ponderosa* |
| Quaking aspen | *Populus tremuloides* |

# Appendix

## Common and Scientific Names of Plants[1]

continued

| Name in text | Scientific name |
|---|---|
| Sandberg bluegrass | *Poa sandbergii* |
| Shadscale | *Atriplex confertifolia* |
| Snowberry | *Symphoricarpos albus,* and<br>*S. oreophilus* |
| Snowbrush | *Ceanothus velutinus* |
| Spiny hopsage | *Grayia spinosa* |
| Squawapple | *Peraphyllum ramosissimum* |
| Starved milkvetch | *Astragalus miser* |
| Stiff sagebrush | *Artemisia rigida* |
| Subalpine big sagebrush | *Artemisia tridentata spiciformis* |
| Utah juniper[5] | *Juniperus utahensis* |
| Wax currant | *Ribes cereum* |
| Western juniper | *Juniperus occidentalis* |
| Western needlegrass | *Stipa occidentalis* |
| White fir | *Abies concolor* |
| Willow | *Salix* spp. |
| Wyoming big sagebrush | *Artemisia tridentata wyominensis* |

---

[1] Scientific and common names are from Garrison et al. (1976), except as noted.

[2] Hitchcock and Cronquist (1973).

[3] Sheehy (1975).

[4] Holmgren (1972).

[5] Smith (1952).

## WILDLIFE HABITATS IN MANAGED RANGELANDS — THE GREAT BASIN OF SOUTHEASTERN OREGON

**Technical Editors**

**JACK WARD THOMAS, U.S. Department of Agriculture, Forest Service**

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General Technical Report PNW-140
June 1982

13

## Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America

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# REHABILITATING AND ENHANCING STREAM HABITAT:
# 2. FIELD APPLICATIONS

GORDON H. REEVES and TERRY D. ROELOFS

U.S. Department of Agriculture Forest Service
Pacific Northwest Forest and Range Experiment Station

# ABSTRACT

Current techniques for rehabilitating and enhancing habitat to increase natural production of anadromous salmonids in the Pacific Northwest and Alaska are described. Methods to enhance spawning, rearing, and riparian habitat, and to improve access are reviewed. The information was compiled from published literature, unpublished reports by State and Federal agencies, and personal communications, including visits with project personnel. Protection of habitat is the best investment for sustaining anadromous salmonid production, but rehabilitation and enhancement projects in the Pacific Northwest and Alaska have sometimes shown encouraging results.

KEYWORDS: Fish habitat, habitat improvement, salmonids, anadromous fish.

USDA FOREST SERVICE
General Technical Report PNW-140

# INFLUENCE OF FOREST AND RANGELAND MANAGEMENT ON ANADROMOUS FISH HABITAT IN WESTERN NORTH AMERICA

William R. Meehan, Technical Editor

## 13. Rehabilitating and Enhancing Stream Habitat:
## 2. Field Applications

GORDON H. REEVES AND TERRY D. ROELOFS
Fisheries Department,
Humboldt State University,
Arcata, California

Gordon H. Reeves, present address is
Department of Fisheries and Wildlife,
Oregon State University,
Corvallis, Oregon 97331.

1982

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
Forest Service, U.S. Department of Agriculture, Portland, Oregon

# PREFACE

This is one of a series of publications on the influences of forest and rangeland management on anadromous fish habitat in western North America. This paper describes methods for rehabilitating and enhancing habitat currently being used and evaluated. Our intent is to provide managers and users of forests and rangelands with the most complete information available for estimating the consequences of various management alternatives.

In this series of papers, we will summarize published and unpublished reports and data as well as the observations of scientists and resource managers developed over years of experience in the West. These compilations will be valuable to resource managers in planning uses of forest and rangeland resources, and to scientists in planning future research.

Previous publications in this series include:

1. "Habitat requirements of anadromous salmonids," by D. W. Reiser and T. C. Bjornn.

2. "Impacts of natural events," by Douglas N. Swanston.

3. "Timber harvest," by T. W. Chamberlin.

4. "Planning forest roads to protect salmonid habitat," by Carlton S. Yee and Terry D. Roelofs.

6. "Silvicultural treatments," by Fred H. Everest and R. Dennis Harr.

7. "Effects of livestock grazing," by William S. Platts.

8. "Effects of mining," by Susan B. Martin and William S. Platts.

11. "Processing mills and camps," by Donald C. Schmiege.

12. "Rehabilitating and enhancing stream habitat: 1. Review and evaluation," by James D. Hall and Calvin O. Baker.

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COMMON AND SCIENTIFIC NAMES OF TROUT, SALMON, AND CHARS--FAMILY SALMONIDAE[1]

| Common name | Scientific name |
|---|---|
| Pink salmon | *Oncorhynchus gorbuscha* (Walbaum) |
| Chum salmon | *Oncorhynchus keta* (Walbaum) |
| Coho salmon | *Oncorhynchus kisutch* (Walbaum) |
| Sockeye (kokanee) salmon | *Oncorhynchus nerka* (Walbaum) |
| Chinook salmon | *Oncorhynchus tshawytscha* (Walbaum) |
| Cutthroat trout | *Salmo clarki* Richardson |
| Rainbow (steelhead) trout | *Salmo gairdneri* Richardson |
| Atlantic salmon | *Salmo salar* Linnaeus |
| Brown trout | *Salmo trutta* Linnaeus |
| Arctic char | *Salvelinus alpinus* (Linnaeus) |
| Brook trout | *Salvelinus fontinalis* (Mitchill) |
| Dolly Varden | *Salvelinus malma* (Walbaum) |
| Bull trout | *Salvelinus confluentus* (Suckley) |

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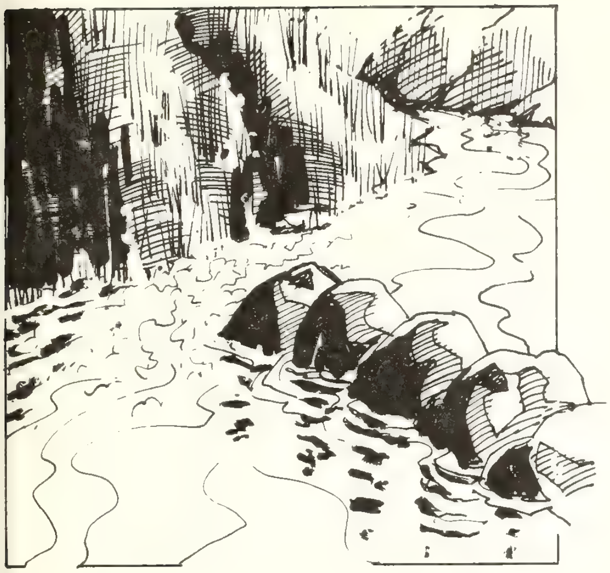
[1] From "A List of Common and Scientific Names of Fishes from the United States and Canada," American Fisheries Society Special Publication No. 12, Fourth Edition, 1980, 174 p.



# INTRODUCTION

Two papers in this series describe methods to rehabilitate or enhance habitat in Pacific Northwest and Alaska streams to increase natural production of anadromous salmonids. Our review and that of Hall and Baker (1982) originated independently; they were circulated for review at about the same time. The paper by Hall and Baker reviews past efforts--successful and unsuccessful, and this paper emphasizes techniques that can be used to rehabilitate or enhance habitats.

Much of the information in this paper was gathered from visits in 1978 to as many projects as possible. Because of time and budget restrictions, we also relied heavily on written or phone contact with those working on rehabilitation and enhancement projects. These people are important sources of information because relatively few evaluations have been published. Some people we could not reach, many of whom probably have much to offer from years of experience. Methods of rehabilitation and enhancement are continually being tested and modified.

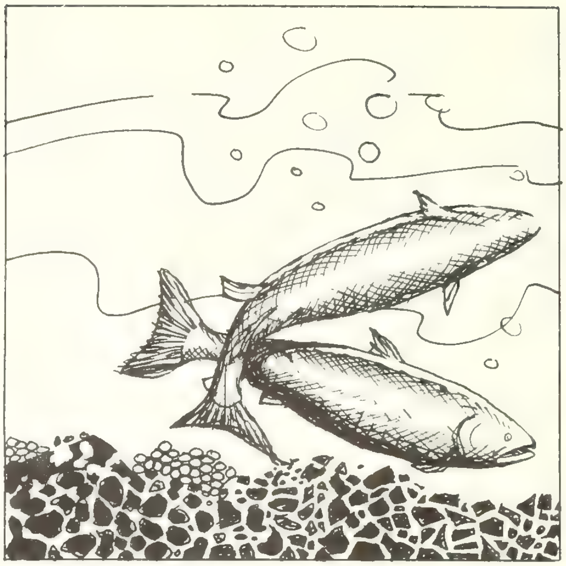
Habitat rehabilitation, as used in this report, means repair of abused or deteriorated habitat by expending energy to augment and speed up natural recovery. Enhancement means creating more suitable habitat than would occur naturally in a stream. This includes increasing access as well as directly improving or developing spawning and rearing habitat. We restricted the study to techniques or projects readily available to fisheries biologists and other resource managers.

Many of the techniques for rehabilitating or enhancing habitat evolved from work on resident trout streams in the Midwest. Hall and Baker (1982) reviewed the history of this work. After much trial and error, some of the methods have been successfully adapted to west coast streams.

We have tried to characterize attributes of successful projects that incorporated biology, hydrology, and engineering into habitat rehabilitation and enhancement. These may not be the only or the best ways to design a structure or to use a method. Rather, we summarize techniques that were successful in given situations as a point of departure for future efforts. A successful practice in one place may not necessarily succeed in another; adjustments and adaptations will have to be made.

Procedures are included in only one section of this paper for convenience; this does not mean the procedure has only one use. Many techniques serve other than the primary purpose. Gabions, for example, are discussed in the spawning habitat section, but they also provide rearing habitat for juvenile fish, help control streambank erosion, and improve fish passage through culverts.

At any time, natural production of anadromous salmonids is limited by some environmental variable or combination of variables (for example, the quality and quantity of spawning gravel, or stream-rearing conditions that might include total area, in-stream cover, food supply, temperature, and other water-quality parameters). Programs to rehabilitate or enhance habitat should not be started until the factors limiting production in a given stream have been identified and evaluated. If, for example, salmonid production is restricted by suitable rearing area, nothing will be gained by enhancing spawning habitat.



# METHODS FOR REHABILITATION AND ENHANCEMENT

## SPAWNING HABITAT

Anadromous salmonids require good spawning habitat to reproduce successfully (Reiser and Bjornn 1979, Shirazi and Seim 1979). Loss of natural spawning areas as a result of human activities--such as dam construction, logging, road construction, livestock grazing, and mining--has undoubtedly contributed to the decline of wild salmonid populations. Cordone and Kelley (1961), McNeil and Ahnell (1964), Wickett (1968), and Platts (1972 unpubl.)[1] have documented the reduction of wild salmonid stocks from sediment deposition in spawning habitat. Rehabilitation of damaged spawning areas has become a common need in all areas of the Pacific Northwest and Alaska.

---

[1] Unpublished references are listed after the Literature Cited.

## Restoration of Gravel

Hydraulic gravel-cleaner.--The history of a hydraulic gravel-cleaner called the "Riffle Sifter" has been reviewed by Hall and Baker (1982). Researchers at Washington State University have modified it and are experimenting with hydraulic jets to dislodge fine sediment from gravel (Mih 1977 unpubl., 1978a unpubl., 1978b unpubl., 1979). Jet nozzles of various sizes, mounted at different heights and angles, are being evaluated for effectiveness in removing fine sediment.

Bulldozer.--The Washington Department of Fisheries has successfully used a bulldozer to reduce concentrations of fine sediment (less than 0.8 mm) in several important spawning areas for pink and chum salmon along Puget Sound (Heiser 1972a unpubl.). In a 1969 pilot study, 1840 $m^2$ (2200 $yd^2$) of heavily silted spawning gravel in the lower Dungeness River were cleaned with a bulldozer by adapting a technique used on the Qualicum River, British Columbia (Heiser 1972a unpubl.). Gravel was turned to a depth of 25-35 cm (10-14 in) as the bulldozer quartered at a 45° angle across the stream, moving into the flow (fig. 1). The blade was tilted and angled like a plow (Gerke 1973). Succeeding passes were made downstream, stepwise, at intervals of 1.5-2.1 m (5-7 feet), so that displaced fine sediments would not be deposited in the cleaned areas. Content of fine sediment was reduced dramatically, and mass spawning of pink salmon occurred in the fall (Heiser 1972a unpubl.). Fry survival was 90-percent greater in the cleaned area than in adjacent uncleaned areas. Total project cost was about 16 cents/$m^2$. The Washington State Department of Fisheries has recently stopped using bulldozers for

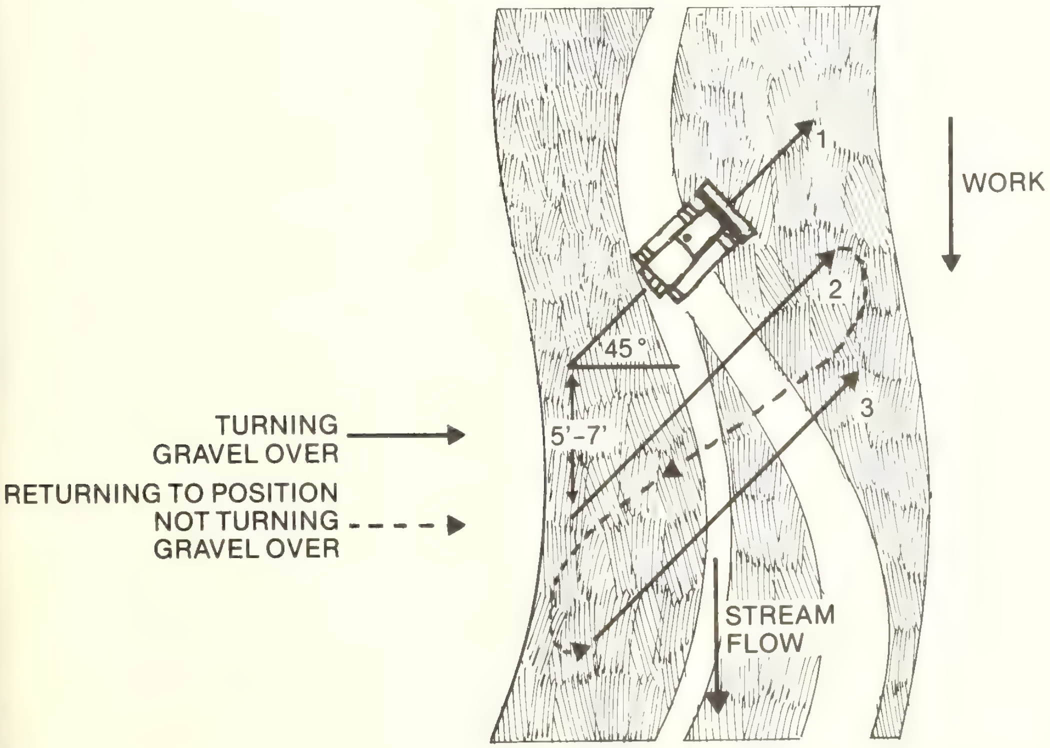


Figure 1.--Cleaning spawning gravel by bulldozer.

cleaning gravel and is planning to use the hydraulic cleaner in its place (Cowan, personal communication).[2/]

Rehabilitating spawning habitat with a bulldozer has been successful only after the source of fine sediments has been stabilized or eliminated, which may require directing efforts at a single point source or toward an entire drainage basin. Such rehabilitation projects have been limited to downstream areas, because dislodged sediments washed downstream could degrade other spawning habitat (Wilson, personal communication). Best results were obtained during the highest water flows in which the bulldozer could be operated safely (Heiser 1972b unpubl.). The depth to which the gravel needs to be cleaned depends on what species use the area; several passes may be required to reduce fine contents adequately (Heiser 1972b unpubl.).

Use of heavy equipment precludes this technique on most small streams.

Manual release of sediment.--On small streams where heavy equipment cannot be used, fine sediments can be dislodged from spawning gravel with a portable pump and fire hose (Wilson, personal communication). A stream of water is directed at the streambed, and displaced materials are washed downstream by the current. Adequate flows are needed to transport the sediment from the area, and sites have been restricted to lower reaches of the watershed.

## Placing and Catching Gravel

Bedload materials are constantly transported from headwaters to lower river areas and may eventually be removed from the system. A sort of equilibrium develops, in which gravel is continually moved downstream by peak flows at about the same rate it is replenished from upstream (Engels 1975 unpubl.). This process can be disrupted by dam construction, debris-jam formation, extreme hydrologic events, and similar disturbances. In other systems, gravel recruitment from natural sources is limited, or the stream lacks the hydraulic environments for well-sorted deposits of gravel. Fisheries managers have used several approaches in attempting to solve these problems.

Placing gravel.--All dams block the downstream movement of bedload materials. Keswick and Shasta Dams on the Sacramento River and Lewiston Dam on the Trinity River in northern California blocked gravel recruitment from upstream, resulting in the loss of important spawning areas for chinook salmon and steelhead trout downstream from these structures. Gravel is introduced annually by the California Department of Fish and Game into the Sacramento River to replace gravel removed naturally (Marriott, personal communication).

In 1976 and 1977, the Trinity River Task Force introduced $500,000 worth of gravel into selected sites on the Trinity River below Lewiston Dam (Lentz, personal communication). Because flows are regulated, much of this gravel has remained in place, but its use for spawning is unknown. A study is now being conducted to determine survival and hatching success of chinook salmon eggs introduced in these areas.

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[2/] A directory for personal communications is provided at the end of the paper.

Gravel placement has successfully rehabilitated two streams in northeastern Oregon damaged by dredge mining (Claire, personal communication). Log barriers stabilized the introduced gravel. This approach has limited applicability and should be used only when degradation is severe and natural gravel recruitment is poor. Introduced material should be of appropriate sizes for the species present. Repeated introductions may be required.

Gabions.--Fishery managers on the Pacific coast have been reluctant to use gabions. Problems associated with their use to collect and hold spawning gravel have been structural instability, failure to retain material of adequate size, and blockage to upstream movement of fish at low flows. Calhoun (1966) stated, "Instream devices are generally considered impractical on the Pacific coast of North America because they cost so much, because they are short-lived, and because stream mileages are so immense." Evaluation of recent gabion installations has not corroborated this pessimistic view, however.

Personnel at the Eugene, Oregon, District of the Bureau of Land Management (BLM) have attempted to modify gabion designs to provide fish passage at low flows on the Siuslaw River. Gabion baskets were extended from each bank with an opening in the center. Another basket, slightly larger than the opening, was positioned on the upstream side of the large wings (fig. 2). Although fish could pass, introduced gravel was carried away by high flows and natural materials failed to accumulate behind the structure.

Failure of some gabions to retain introduced gravel should not be entirely attributed to design or structural failures (Anderson and Cameron 1980). Gravel introduced into a stream is usually cleaned and washed free of fine sediment. These smaller particles may act as a binder, helping retain and stabilize larger material in natural situations. Their absence may be responsible in part for failures of some gabions to retain gravel.

Wilson (1976) stated, "One problem that has occurred with stabilization, and to a lesser extent with some of the gravel replacement projects, is stabilization of gravel during the first year's high flows. The mechanical disturbance of the streambed during construction and the change of gradient cause the streambed materials to establish a new equilibrium within the physical constraints of the stream. Spawners

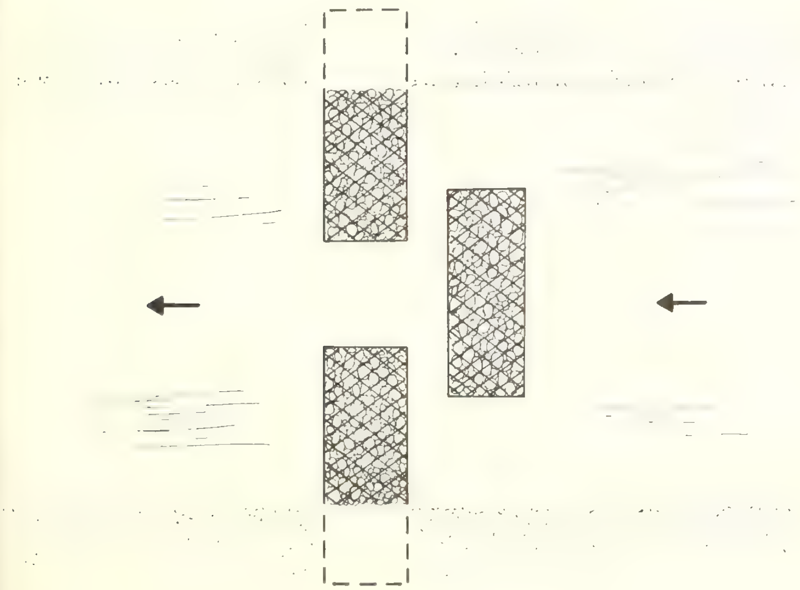


Figure 2.--Gabion design used unsuccessfully on tributaries to the Siuslaw River, Oregon (Hammer, personal communication).

seem to sense this instability and tend to avoid an improved area the first year after it is in use."

Some "weathering" of gravel is required before it is accepted by spawners (Dames and Moore, Inc. 1978 unpubl.; Wilson, personal communication). The accumulation of smaller materials in the gravel probably provides the stability and weathering necessary to attract fish. Platts et al. (1979) found that spring and summer chinook salmon in the Salmon River drainage of Idaho consistently built redds in areas where the particle size of most of the sediments was less than 19 mm (0.75 in).

Recent modifications in the design of gabions have led to significant improvements in accumulation of gravel that has been widely used by steelhead trout. The Coos Bay District of BLM has installed V-shaped structures, rather than the more conventional method of placing the gabion across the stream perpendicular to the flow (Anderson and Cameron 1980) (fig. 3). Ehlers (1956) found that V-shaped log structures were the most successful on the East Fork of the Kaweah River, California.

The ends of the gabion are toed 1-1.5 m (3-5 feet) into the banks and riprapped to prevent flows from washing around the ends. Sections are cabled together and the entire structure is cabled to large trees or rocks near the banks (Anderson, personal communication). Slanting slightly downward toward midstream, these V-shaped structures dissipate the energy of flowing water better, reduce bank erosion and therefore the chances of wash-out, and create better pools. The gabion weirs are placed in series; the upstream structure dissipates the energy of the water by creating a drop, and the downstream weir accumulates and retains gravel. Best results have been obtained when the bottom of the

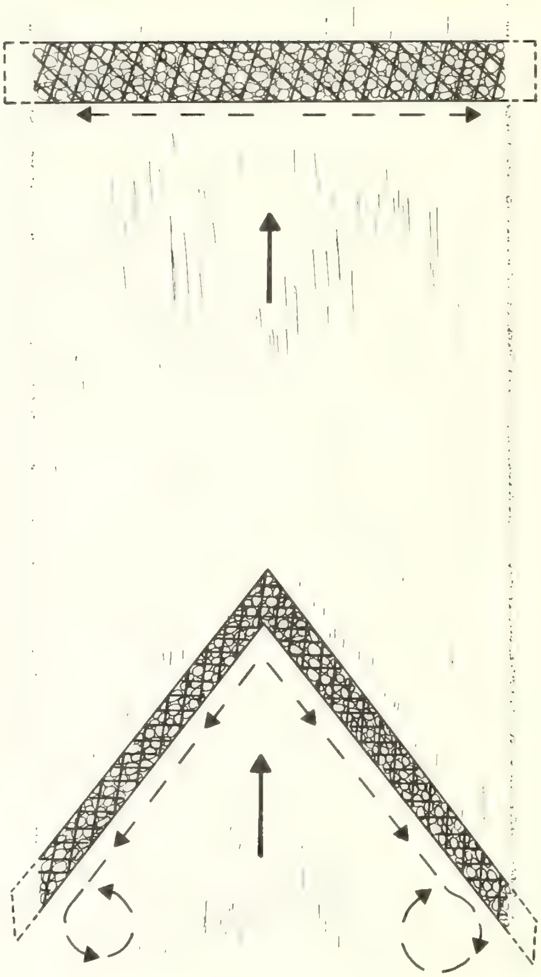


Figure 3.--Comparison of the conventional, perpendicular gabion weir and the V-notched design used by the Coos Bay, Oregon, District BLM. In the conventional design, water deflects to the side, washing around the end and weakening the structure. Flow is concentrated to the center of the V design, and deflected flows form back eddies (Anderson, personal communication).

upstream weir was level with the top of the downstream structure. Figure 4 shows the results of incorrectly placed gabions. Gravel deposition occurs only in a small area near the downstream structure when weirs are generally in the same plane. When the downstream weir is too low, inadequate pools form below the upstream structure, and gravel eventually fills in the pool. Best results have been obtained when the upstream structure was at a point where the stream begins to widen naturally (fig. 5). This further dissipates the energy of the water. The downstream gabion is situated immediately upstream from the natural channel constriction where water begins to pick up energy again (Anderson, personal communication). Placement on sharp bends should be avoided because this aggravates bank cutting and gravel scouring (Wilson 1976; Anderson, personal communication).

These V-shaped gabions have worked best on slopes of 1.5 to 2 percent, but have also been used on steeper gradients with some success (Anderson, personal communication). The most successful structures in the Siuslaw River drainage were located in tandem and reduced the local gradient to 1 percent (Engels 1975 unpubl.). Gabions on the Siuslaw River were anchored to the streambed with large metal pins. An unforeseen problem developed when the structures overturned or washed out; some pins, left intact, have posed hazards for boaters (Hammer, personal communication).

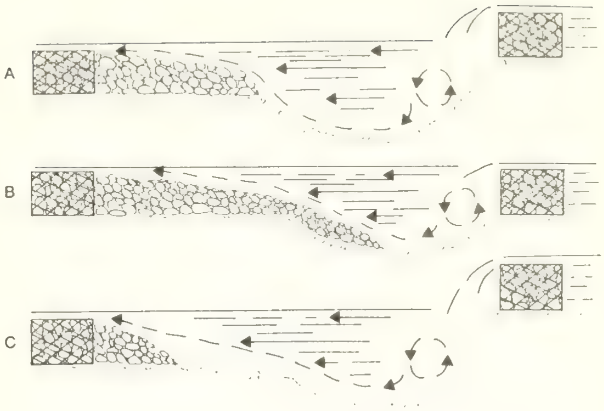


Figure 4.--Gabion placement. Good spawning conditions develop when the top of the downstream gabion is about level with the bottom of the upstream weir (A). When the downstream structure is too high relative to the upstream structure, no pool is formed (B). In C, the downstream weir is too low, so little gravel is accumulated and a large pool is formed (Anderson, personal communication).

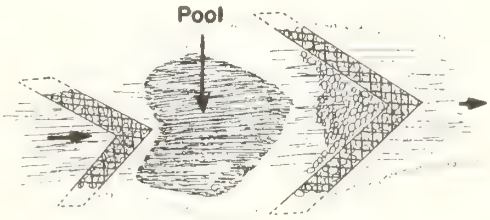


Figure 5.--Series of gabions, showing the function of individual weirs. The upstream structure is placed just upstream from where the channel widens. The downstream gabion is located upstream from the natural channel constriction. The upstream gabion dissipates the energy of the flowing water; gravel accumulates and is retained behind the lower structure (Anderson, personal communication).

Production of pink and chum salmon in Puget Sound streams was often limited by insufficient quantities of gravel and by shifting and scouring of streambed materials (Heiser 1972a unpubl.). An experimental program began in the late 1960's to enhance spawning habitat (Gerke 1973). Development of enhancement techniques was concentrated on a few streams; early work included the use of log weirs, rubber tires, and large rock, but gabion weirs most effectively stabilized and retained gravel. Gabion baskets did not crack, shift, or break if the substrate settled; because of their flexibility, they conformed to streambed changes (Gerke 1974). Sharp, angular quarry rock was the best fill material for gabions and formed the most stable structures (Wilson, personal communication). Rounded, river-run material tended to shift more readily, reducing the stability of a structure. Similar results were also reported by Engels (1975 unpubl.) in Oregon. Gabion baskets were lined with heavy plastic sheeting before being filled. The plastic lining prevented water from percolating through rather than over the gabion. This aided fish passage when water flow was low. Gabions lined with plastic also accumulated debris and sediment more quickly, filling interstices and helping to stabilize the structures (Wilson, personal communication).

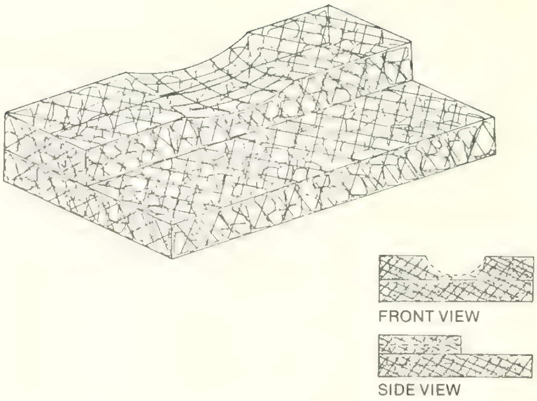


Figure 6.--Two-tiered gabion weir used to accumulate and stabilize spawning gravel in various Washington streams. Note notch in center to allow fish passage at low flows (Wilson, personal communication).

Streambed material in these Washington streams is conglomerate and much less stable than material found in the sandstone bedrock streams of Oregon. Structures like those in figure 6 have been the most suitable and long lived. A standard basket--0.3 m deep by 1.5 m wide by desired length--is filled and set in the substrate so that the top is level with the streambed to form a base and splash apron. Baskets that are 0.3 m high by 1 m wide by desired length are then wired to the upstream half of the the apron so that the downstream portion of the lower basket prevents undercutting and thus increases stability. A slot 1.5 m wide and 0.13 m deep is constructed in the center of the upper basket to ensure fish passage at low flows (Gerke 1973). When gabions were incorrectly constructed or located, dams--similar in structure to the weirs but with a large opening in the center--were built immediately downstream to create pools to allow upstream movement (Wilson, personal communication). Ends of the gabions are toed 1-1.5 m into each bank and riprapped with rock there and upstream to prevent bank erosion and washout. Riprapping must not constrict the natural channel (Wilson, personal communication).

Structures are located in series at each 0.3-m drop in stream elevation. They are built high enough to obtain the optimum gradient for the desired species, usually 0.2-0.3 percent for pink and chum salmon (Wilson, personal communication). Experience has shown that structures with single 0.3-m-high baskets built in series to the desired height are more stable than a single, deeper basket (Wilson, personal communication). For example, if 0.6 m is the height required, two 0.3-m baskets would be more stable than a single 0.6-m basket.

Where natural materials are lacking, gravel is introduced and roughly graded into place. Gravel retention and gradient control have been successful on some fairly steep gradients. For example, ten gabions were located on Johns Creek, a tributary of the Hamma Hamma River, Washington, where a 3-m change in elevation occurred in 222 m (Wilson, personal communication).

Longevity of gabions has depended on the experience of the biologists, hydrologists, geomorphologists, engineers, and construction crews designing and building the structures, as well as on the stability of the watershed (Anderson, Wilson, personal communications). Successful use of gabions has depended to a great extent on trial and error and on knowledge gained from past mistakes. As with gravel-cleaning operations, best results with gabions have been achieved on stable watersheds.

Rock and log sills.--In 1972, the Oregon Fish Commission built a series of rock sills on lower Anvil Creek, a major spawning tributary of the Elk River used by chinook salmon on the central Oregon coast (Bender 1978 unpubl.). Large boulders were bulldozed together across the stream channel so that silt and debris could lodge among rocks to form pools and collect spawning gravels. The structures failed when high flows removed underlying materials (Bender and Mullarkey, personal communication).

Five log sills (fig. 7) were constructed by Oregon Fish Commission personnel to replace the rock structures in the summer of 1973--at a total cost of $1,800 (Bender 1978 unpubl.). Large logs were partially set into the streambed and extended into the banks, where they were anchored with riprap. Support posts were angled into the streambed (parallel to the flow) and nailed to the logs. Gravel was bulldozed behind each structure and sloped to the top. Cyclone fencing was overlaid on the posts and attached to both posts and logs for stability.

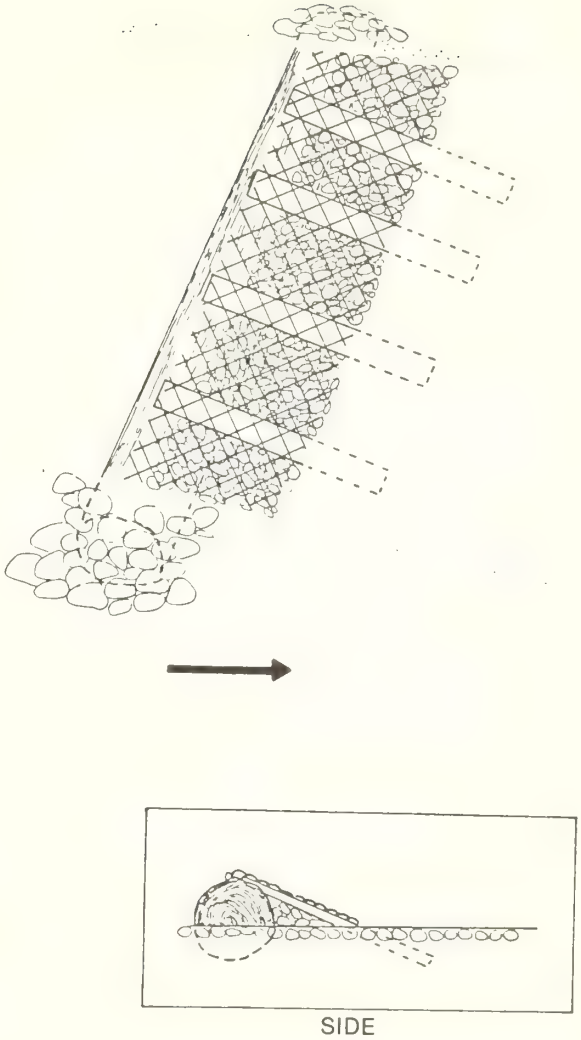


Figure 7.--Log sills used by the Oregon Fish Commission to collect spawning gravel for chinook salmon on lower Anvil Creek. Support posts are attached to the main log and anchored in substrate. Gravel is placed on top of log and sloped back. Cyclone fencing is then laid over and attached to the log and support posts (Bender and Mullarkey, personal communication).

Gravel accumulated behind the structures during the first winter and was readily accepted by spawning chinook salmon and steelhead trout. Emerging fry move almost immediately into the Elk River and estuary nursery areas; as a result, little rearing habitat is required in Anvil Creek. This situation and the pristine condition of the watershed have probably been largely responsible for the success of the project (Bender and Mullarkey, personal communication).

Cedar-board structures.--The Coos Bay District BLM has designed and built cedar-board structures (fig. 8) on small streams to accumulate gravel and provide holding areas for adult steelhead trout and rearing pools for juveniles (Anderson, personal communication). These structures, placed in series, have been considered quite successful. A main support log is laid across the stream and anchored into the banks. An open-ended "V" is formed by attaching two more supports to the first log and angling one into each bank. Shakes (here made of readily available cedar) 2-2.5 cm thick are secured to the side supports and slanted down into the streambed. They rise slightly above winter flow levels so that most of the water flows to the center to make better pools. Additional shakes are set at right angles to the main support (paralleling the streambanks) between the side supports. The downstream edge of an upstream shake should overlap the upstream edge of a downstream shake to prevent shake displacement by high flows (Anderson, personal communication). Construction and installation is inexpensive and quick because most necessary materials can be found near the sites.

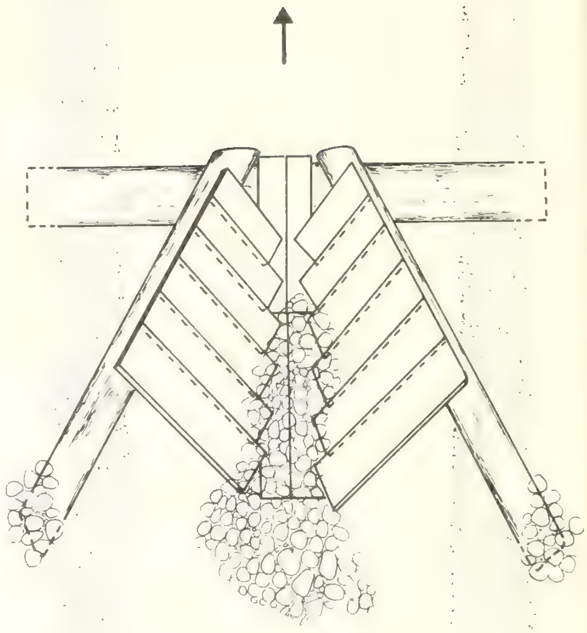


Figure 8.--Cedar-board structures designed by the Coos Bay, Oregon, District BLM to accumulate spawning gravels and create holding pools in small streams (Anderson, personal communication).

## Minimizing Impact of Projects

Possible adverse impacts on fish and other organisms during project construction must be considered. Environmental impacts of projects to improve spawning habitat in Washington have been minimized by confining the work to periods when little fish activity occurs (Dames and Moore, Inc. 1978 unpubl.). These Washington streams were used mostly by pink salmon, chum salmon, or both; avoiding some initial adverse impact will be more difficult, however, in areas inhabitated throughout the year by anadromous salmonids.

In-stream work--such as gravel cleaning, gravel placement, and gabion or riprap placement--causes temporarily increased suspended solids and turbidity downstream. These suspended materials can reduce benthic invertebrate populations and fish spawning success in lower sections (Dames and Moore, Inc. 1978 unpubl.). Areas disturbed by project activities, however, are repopulated quickly by invertebrates and algae from unaffected regions upstream (Dames and Moore, Inc. 1978 unpubl.; Meehan 1971).

Some destruction of riparian vegetation occurs along stream sections where work occurs and in areas required for access (Dames and Moore, Inc. 1978 unpubl.; Wilson, personal communication). Damage can be minimized by careful selection of access routes, by avoiding bank disturbance, and by reseeding and replanting.

## Further Considerations

Several factors should be considered before projects to improve spawning habitat are undertaken. Best results are obtained on stable watersheds where erosion and runoff problems are minimal. Good drainage-basin conditions have contributed substantially to much of the successful work discussed in this section. History of an area's use by adult and juvenile fish must be evaluated. Streams used in the past that had developed reduced runs for whatever reason have shown the best response. In some areas where stocks have been eliminated or never recorded, fish may be introduced after rehabilitation or enhancement. Accessibility for necessary equipment must also be taken into account.

The literature and many of the people interviewed present pessimistic views of projects for improving spawning habitat, especially those using gabions. A reluctance to attempt any type of project is evident, because of fear of failure from catastrophic natural events, or limitations of the structures and techniques. Techniques applied successfully in one area may not be directly applicable in others. Principles derived from these efforts, however, can be modified to meet specific requirements, by using creative thinking and trial-and-error experimentation.

## REARING HABITAT

Preferences and requirements of juvenile anadromous salmonids for rearing habitat have been studied by numerous authors, as reviewed by Reiser and Bjornn (1979). In the past decade, efforts have been made to enhance freshwater rearing areas as a means of increasing fish production.

## In-Stream Cover

Studies are underway to evaluate various structures and techniques for increasing in-stream cover to enhance salmonid production. As part of such a program in British Columbia, replicated designs of boulder and gabion V-notched weirs and deflectors, deflectors and cover, and helicopter-placed boulders were located in 1977 in the upper Keogh River, on Vancouver Island (Ward and Slaney 1979). In 1978, 33 additional structures were installed by helicopter, including boulder groupings or clusters with and without cabled log cover. Costs of placement by helicopter were about the same as with conventional heavy machinery if the cost of access roads was included. Flow differences between years may have inflated initial results because of fish dispersal. Confirmed results showed that gabions and deflectors without log cover were relatively unsuccessful, but boulder groups were both successful and cost effective (Ward and Slaney 1979). Everest (personal communication) noted in some sites that the cabled logs intended to provide cover were apparently not effective during high water. The logs moved up and down in the water column and failed to reduce water velocity beneath them at higher flows. This problem was alleviated by recabling logs to the larger lead boulder in the cluster. Whether or not these log additions are cost effective, however, is uncertain (Slaney, personal communication).

Another study is underway on Colquitz Creek, a small urban stream on Vancouver Island, to determine the relative contribution of habitat alteration to survival of over-wintering coho salmon and cutthroat trout and to assess the permanence of habitat-improvement structures (cobble and boulders, anchored root wads, and rock and root wads) on small coastal streams (British Columbia Fish and Wildlife Branch, Fish Habitat Improvement Section 1977 unpubl.). Structures have remained stable, but fish use and cost effectiveness have not been evaluated.

Placing of boulders.--On the South Fork of the John Day River in Oregon, boulders 0.45-1.1 m in diameter were placed by a large, front-end loader in areas that contained no salmonids (Claire 1978a unpubl.). Introduced rocks were set in patterns similar to those occurring naturally in areas with salmonids. This arrangement was chosen in the absence of knowledge about what patterns would be best and to minimize damage to the appearance of the river. Additional rocks were placed in open stream areas and near overhanging trees. Cutbanks were riprapped, and rock deflectors were placed where current deflection was needed. Juvenile salmonids have now been found in the improved area (Claire 1978a unpubl.).

Boulders placed in Redcap Creek, a Klamath River tributary in California, increased both numbers and biomass of age 1+ steelhead over 300 percent above control sections (Brock 1981).

A highway realignment project on Beech Creek, near Mount Vernon, Oregon, resulted in numerous channel changes and deep cuts through bedrock. Boulders placed in steep areas reduced water velocities and created pools and gravel bars used by spawning and rearing steelhead trout (Claire 1978a unpubl.).

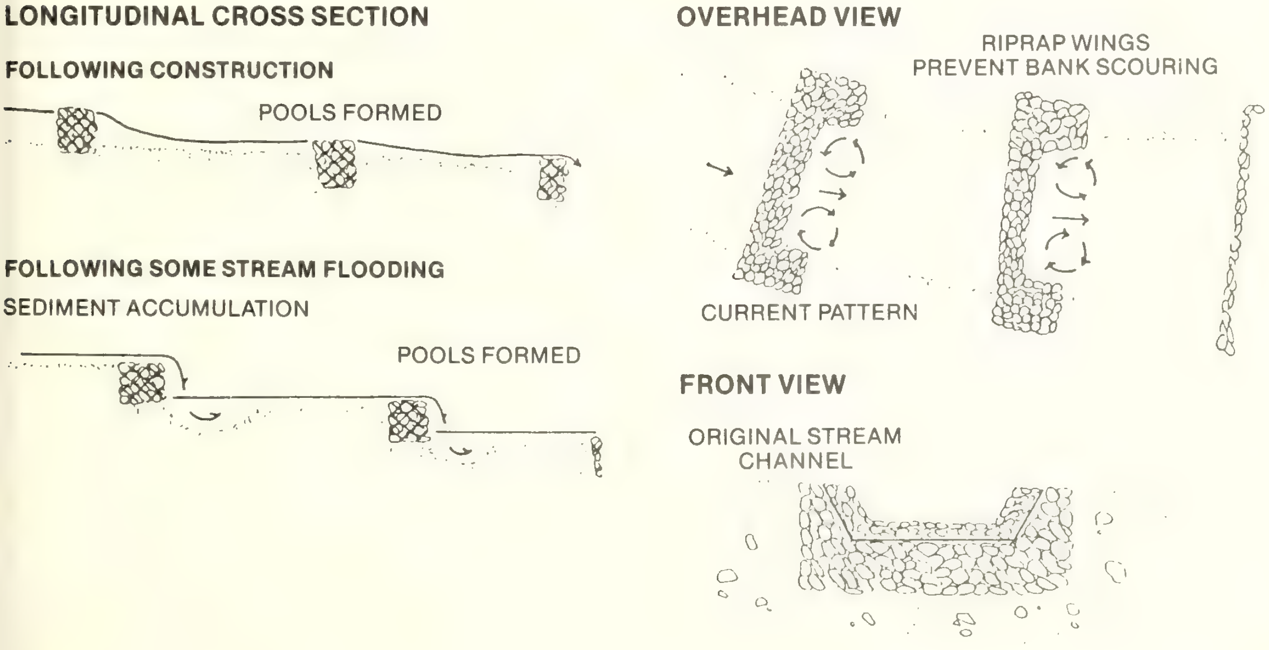
The substrate on which rocks and boulders are placed must be stable enough to prevent the large rocks from being buried by undercutting (Claire, personal communication). Hydrologists and geomorphologists should help plan these projects to ensure their success. Although boulder placement may be one of the more worthwhile enhancement techniques in the Pacific Northwest, potential problems should not be overlooked. For example, an overabundance of newly placed boulders might inhibit natural stream flushing of sediments, and alteration of natural patterns of stream meander could cause erosion problems on newly formed stream curvatures.

Rock-drop structures.--The pool-riffle sequence is regarded as the basic unit of the stream environment (Mundie 1974). Alteration of this pattern can adversely affect fish populations (Whitney and Bailey 1959, Johnson 1964, Elser 1968). Fifteenmile Creek is a Columbia River tributary near The Dalles, Oregon. After a 100-year flood in 1964, the stream course was straightened and channelized, and riparian vegetation was removed along most of eight stream kilometers west of Dufur, an important steelhead trout spawning and rearing area (Newton, personal communication). Increased erosion resulted, and steelhead trout use decreased drastically.

After another 100-year flood occurred in 1974, the local soil and water district received Federal funds (Fund 216--Small Watershed Restoration) for extensive streambank stabilization. The project included funds for streambank fencing and rock-drop structures to enhance stream recovery for anadromous and resident trout populations (Newton, personal communication).

The rock-drop structures (fig. 9), still intact after three seasons, were constructed to control stream gradient and to form pools for rearing and holding steelhead (Newton 1978 unpubl.). A series of trenches was excavated across the channel and into the banks with a backhoe. The trenches were filled with angular riprap rock to a height of 0.45 m above the streambed. Pools formed above the structures filled with gravel and silt during the first winter, and new pools scoured out below each structure. The only adult steelhead trout observed within the Dufur Valley the first spring after installation were in the newly created pools (Newton, personal communication). Steelhead trout redds were also observed near the drop structures. Juveniles have used the area for rearing; interstices in the structures also provide a refuge.

Figure 9.--Rock-drop structures constructed by the Oregon Department of Fish and Wildlife on Fifteenmile Creek, Oregon (Newton, personal communication).



Another benefit of these structures has been to control channel and streambank erosion. Arranged in tandem, they reduce flow velocity and dissipate much of the erosive force at the plunge over the structure (Newton, personal communication). About 1 m of water flowed over the structures in the winter of 1977 without any appreciable streambank erosion.

Exclusion of livestock and revegetation of damaged streambanks were undertaken in conjunction with drop-structure placements. The drop structures have also stabilized streambanks.

Log weirs.--Several log weirs, designed to create rearing habitat, have recently been installed in a stream on the Umatilla National Forest in eastern Oregon. The success of the project has been attributed to the large logs (up to 1.2 m in diameter and 20 m long) anchored 4-5 m into the streambank. The streambank has been armored with large rock near the weirs. Hardware cloth and plastic sheeting are placed over this substrate. Preliminary evaluation has indicated greatly increased use by juvenile chinook salmon and resident trout (Andrews, personal communication).

Half-log structures.--Half-log structures have proved successful in providing cover for resident trout in Wisconsin (Hunt 1978). These structures consist of a 2- to 2.5-m log cut in half lengthwise, with a hole drilled through the log at each end (fig. 10). A wooden block is placed under each end of the log and a metal stake is driven through the log and block and into the substrate to anchor the structure. The stakes are then bent down on top of the log. Structures should be placed where they will be covered by water at all times to increase their life span. The usefulness of half-log structures as part of a pilot program for improving stream habitat is being investigated on the Shasta-Trinity National Forest in California (Brouha, personal communication).

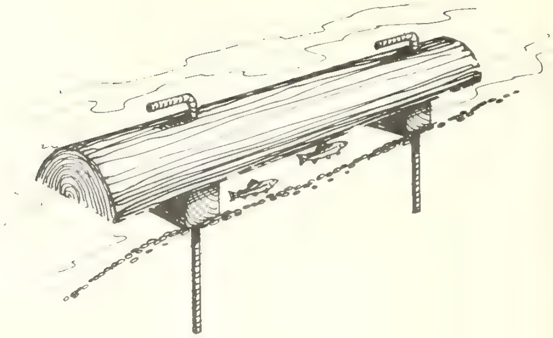


Figure 10.--Half-log structure used in Wisconsin trout streams (Hunt 1978).

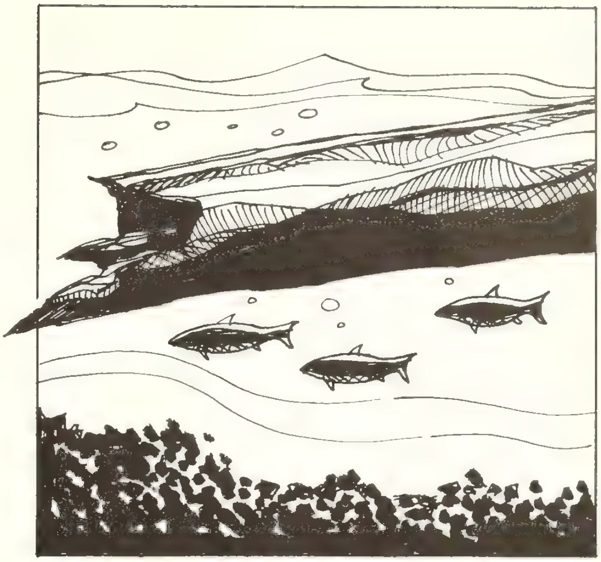
## Irrigation Diversions

Irrigation diversions have caused significant losses of migratory fish throughout the western United States. Steelhead trout and chinook salmon fry and smolts migrating downstream often move into main and lateral irrigation canals and become stranded in fields. Over 161 km (100 miles) of the Salmon River headwaters in Idaho have been affected by such diversions (U.S. Department of Agriculture, Forest Service 1977a unpubl.). During the 1977 irrigation season, the entire flow of about 66 km (41 miles) of productive spawning and rearing habitat was diverted for nearly 4 months (U.S. Department of Agriculture, Forest Service 1977a unpubl.).

As a result of the Columbia River Fishery Development Program, construction of fish screens to prevent irrigation losses began at the lower end of drainages in Idaho in 1958. The Idaho Department of Fish and Game constructed over 225 units by 1977. Not all of the scheduled projects were completed, however. In 1977, the USDA Forest Service became a cooperator in the program.

A diversion screening project was undertaken cooperatively by the Idaho Department of Fish and Game, National Marine Fisheries Services, and the USDA Forest Service to rectify problems in the Sawtooth National Recreation Area. During 1977 and 1978, 52 diversion points were evaluated for construction of screens (Fisher 1977 unpubl.). Some of these sites remain to be investigated to assure a need for screening. The electric rotary-drum design is proposed most frequently for screening. More efficient than the older style "plate and scrubber" screen, it has been in use in Idaho since 1972. Where use of power is too expensive, self-powered paddle wheels can be adapted to drive the drum units (Contreras, personal communication). Beginning experimentally in 1979, fixed screens have been installed and evaluated for use on diversions of less than 5 $ft^3/s$.

Estimates of losses in fish production in the Sawtooth National Recreation Area range from 30 to 80 percent (Contreras 1977 unpubl.). Since 1977, the cooperative program has installed 18 new screens, and about 75 percent of the fry loss has been eliminated. A successful screening program will continue to enhance the survival of downstream migrants and thus increase the number of returning adult spawners. For each 100,000 fry saved, a 1-percent return would net an increase of 1,000 adults for spawning. Similar screening measures have been taken in many other areas to prevent losses to irrigation. Screen design and location are discussed by Clay (1961) and Canada Department of Fisheries and Oceans and British Columbia Ministry of the Environment (1980).



## Rearing Pools

Blasting of pools to enhance rearing habitat has been restricted to streams with a substrate of solid bedrock and rather low, in-channel storage of bedload. The technique has been only somewhat successful. Efforts to create pools in the more typical rubble-cobble substrate streams probably would be unsuccessful because the pools would fill rapidly unless they were designed to ensure hydraulic scouring (that is, with high enough velocities to prevent redeposition of bedload).

Sites with a natural ledge or break in gradient have been selected for pool blasting because they have natural hydraulic scouring and flushing action (Anderson and Miyajima 1975; Heller, personal communication). Stream hydraulics, bedload characteristics, and pool configuration also influenced the locations. Other site and construction criteria are discussed by Anderson and Miyajima (1975).

## Overwintering Habitat

To ensure winter and spring survival and production of fish in intermittent streams, they should be protected in the same way as perennial streams, including the stabilization and revegetation of overhanging banks, and addition of in-stream cover. Enhancement of backwater areas should also be worthwhile, particularly for juvenile coho salmon (Narver, personal communication).

## Justification for Enhancing Rearing Habitat

The suggestion has been made that in-stream enhancement projects merely redistribute fish rather than actually increase the carrying capacity of a stream. The territorial behavior of juvenile salmonids (Keenleyside 1962, Hartman 1965, Everest and Chapman 1972) may ensure that all suitable habitat in an area is occupied. Less dominant fish are forced to emigrate to less desirable areas (Chapman 1962). If an area that previously contained few or no fish is "enhanced" and becomes used, fish will still occupy the unenhanced habitat. Rather than being forced from a system in search of suitable living space, some "nomads"(Chapman 1962) will remain in the area and either establish territories in the improved sections or use the areas formerly occupied by the more dominant fish that have been attracted to the new habitat. An increase in the amount of suitable habitat (for example, cover) will result in more fish and thus increase fish production in a stream.

# RIPARIAN HABITAT

The condition of the riparian zone influences stream temperatures and sediment contents (Hall and Lantz 1969, Burns 1972, Claire 1978b unpubl.). In addition, riparian vegetation and banks provide cover for fish that reduces predation and downstream displacement (Hartman 1965, Chapman and Bjornn 1969, Lewis 1969). Loss of vegetative cover and undercut banks decrease the amount of suitable habitat, thereby reducing stream productivity and carrying capacity for fish (Butler and Hawthorne 1968, Gebhards 1970). Streambank vegetation is also an important source of fish food (Giger 1973, Meehan et al. 1977). Small fish use slower water along margins of larger streams (Chapman 1966, Allen 1969), and depend on terrestrial organisms from streamside vegetation for food, because most of the aquatic drift escapes them (Giger 1973). A recent paper by the American Fisheries Society, Western Division (1980 unpubl.) discusses management and protection of riparian ecosystems.

## Rehabilitating Overgrazed Areas

Leopold (1975) stated that livestock grazing may have cumulative detrimental effects on the productivity of both aquatic and terrestrial ecosystems. Because he believes that adverse impacts of livestock grazing on public lands have been vastly underestimated, he called for long-term studies of multiple use.

Range managers often fail to understand stream ecosystems and fisheries production; sound scientific results showing effects of livestock grazing are lacking. Platts (personal communication) evaluated long-term effects of livestock use on riparian and aquatic habitats and fish populations, including anadromous stocks. Pregrazing data were compiled for 4 years and, beginning in 1979, controlled grazing was allowed. Effects of various grazing strategies on streamside and aquatic communities are being evaluated. The study should provide information that will help minimize future grazing damage to stream ecosystems.

Fencing to exclude livestock has been the primary management technique used by fishery biologists to protect and rehabilitate riparian zones (Ames 1977, Duff 1977 unpubl., Claire 1978b unpubl.). Often, restricting livestock use has resulted in more rapid improvement in riparian areas than anticipated (Winegar 1975, 1977). In severely damaged streams, however, the recovery process may be accelerated by planting grasses, shrubs, and other vegetation (Durbin 1977). Although results are encouraging, fencing is far from a panacea for preventing degradation of the habitat from overgrazing. Gunderson (1968) observed that fencing is not practical along some streams, especially those with wide flood plains. Fencing costs are always high, and maintenance costs can be formidable (Armour 1977 unpubl.). Also, the riparian zone is often more productive of forage than are upslope lands, and its exclusion from grazing results in a substantial reduction in carrying capacity for livestock.

An alternative to complete exclusion of animals is provided by rest-rotation grazing. Unfortunately, restoration of previously damaged riparian zones is apparently provided more by the rest than by rotation. In addition, the natural attraction of streamside areas to livestock drastically reduces the length of time that grazing can be allowed without damage to the aquatic habitat.

## Stabilizing Banks

Rock jetties.--Sloughing and erosion of streambanks reduce cover for fish, and may create sediment problems. In eastern Oregon, rock jetties or deflectors have been more effective than blanket-type riprap placement in protecting and stabilizing damaged streambanks (Claire, Newton, personal communications). Figure 11 shows the series design used. A modification was suggested by Brouha (personal communication) after he visited some jetty placement sites. The jetties should not be spaced at regular intervals along the bend, but closer together toward the downstream end of the bend, where the current is greatest. This prevents back currents from eroding the banks along this section of the bend.

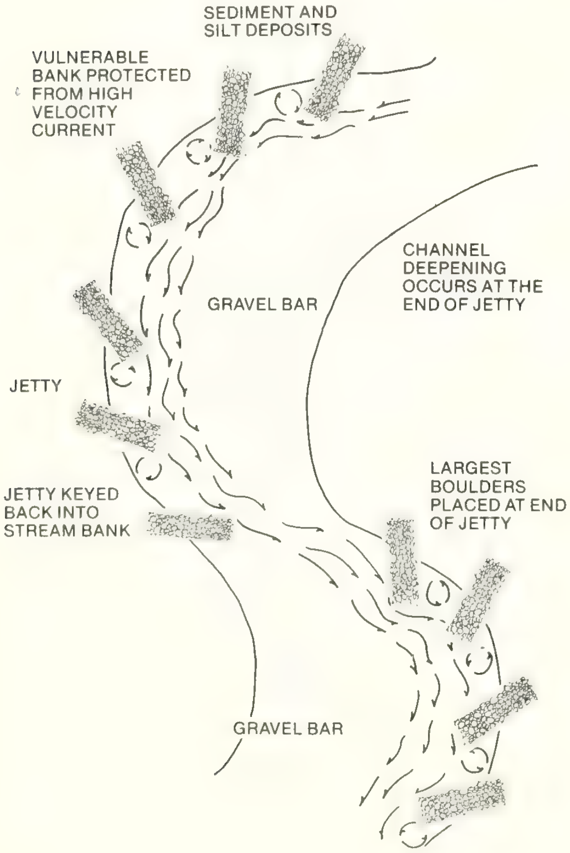

SEDIMENT AND SILT DEPOSITS
VULNERABLE BANK PROTECTED FROM HIGH VELOCITY CURRENT
CHANNEL DEEPENING OCCURS AT THE END OF JETTY
GRAVEL BAR
JETTY
LARGEST BOULDERS PLACED AT END OF JETTY
JETTY KEYED BACK INTO STREAM BANK
GRAVEL BAR

Figure 11.--Rock-jetty series used to reduce bank erosion in eastern Oregon (Newton, personal communication).

Jetties restrict channel width or capacity and are therefore only applicable to large stream channels (Newton, personal communication). The jetty angle must be carefully designed because an improper angle of flow deflection causes additional problems. If the jetty is properly designed, sediment normally accumulates in slack water on the downstream side of the structure and vegetation may grow in the deposited sediment. Pools formed at the end of the jetty are used by fish for rearing and holding. Sometimes gravel has been deposited (fig. 11), and it has been used by chinook salmon for spawning (Claire, personal communication). Jetties also provide access for fishing. Once vegetative growth begins, they are indistinguishable from the natural surroundings.

Juniper riprap.--Cut juniper trees, flattened and anchored along damaged streambanks, have successfully halted bank erosion along the South Fork of the John Day River, Oregon (Sheeter and Claire 1981). Junipers were selected because they are bushy, the wood is durable, and the needles remain on the branches for long periods after the tree is cut. Needles trapped sediment and debris at high flows; up to 30 cm of soil were deposited behind the trees after 1 year. Since the project was completed by the Oregon Department of Fish and Wildlife in 1975, the trees have been compressed against the bank and covered with silt, and no further erosion is evident. Native vegetation has become established, and planted willows have grown to over 4 m. Placing this type of riprap between rock jetties or other current deflectors might further reduce erosion of banks (Brouha, personal communication).

Rock riprap.--Experiments on the Shasta-Trinity National Forest in California (Brouha 1981 unpubl.) will evaluate the use of riprap for stabilizing landslides and slumps resulting from past logging and stream clearance operations, and for restoring the stream channel to a more sinuous form. Responses of fish populations will be monitored.

Revegetation.--Past rehabilitation efforts often included introduction of exotic plants to damaged areas. Experience has shown this is often unnecessary because native vegetation readily invades disturbed areas (Winegar 1977; Barnes, Claire, personal communications). In arid or semiarid areas, replanting vegetation may hasten recovery and ensure that the vegetation is close enough to the stream to be beneficial (Evans, personal communication).

Earth walls.--Hutchison (personal communication) has suggested use of reinforced earth walls as described by Walkinshaw (1975) (fig. 12) to stabilize streambanks and slopes. He also believes earthwall structures could possibly be used as in-stream sills to hold gravel or create wing dams. These structures have been used successfully in highway construction but are untested on streams.[3]

Summary.--Forest practice acts and other land-use laws recognize the importance of the riparian zone and provide for its protection. Enforcement has been lax or lacking altogether, however, so fisheries biologists spend more time attempting to correct past problems than preventing new ones. Most techniques are aimed at protecting areas from further damage while allowing natural revegetation and stabilization. Riparian vegetation can return within a few years, but bank stabilization, depending on the severity of the damage, may take years or even decades.

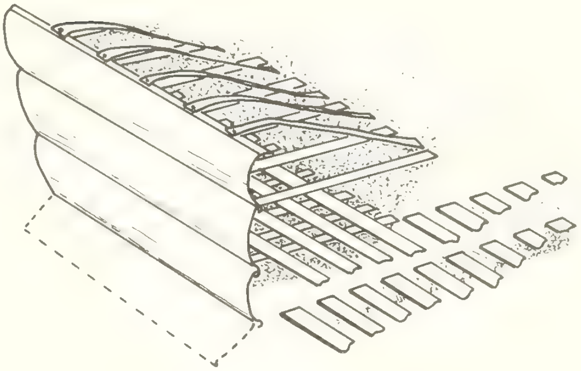


Figure 12.--Diagram of a reinforced earthwall structure. Galvanized steel reinforcing strips, connected to a steel or concrete facing, are covered with a granular backfill. The strips reinforce the soil which is held in place by the internal friction between strips and soil. Depending on the job, the strips are transverse or, where necessary, both transverse and longitudinal (Hutchison, personal communication).

## IMPROVING ACCESS

Access improvement--including removal of debris and log jams, construction of fishways, and installation of culverts--probably has been the most common type of project undertaken to enhance habitat of anadromous salmonids. Evaluation of these efforts has been minimal, however. The absence of assessment or even documentation of many projects makes reviewing and evaluating access improvement difficult.

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[3] Information on these reinforced earth walls can be obtained from the Federal Highway Administration, 610 East Fifth Street, Vancouver, Washington 98861.

## Removing Barriers

Debris jams provide cover for juvenile fish (Bustard and Narver 1975a). Once established, they may be important stabilizing features within streams. Sheridan (1969 unpubl.) recommended consideration of the following factors before debris accumulations or jams are removed:

- Does it seriously impede migration of desired fish?
- Does it remove suitable spawning areas from production?
- What will be the effect on stream gradient and general configuration?

Consideration should also be given to the potential impact on resident fish populations above the barrier. The quantity and quality of rearing habitat being blocked should also be taken into account. When practical, barriers should be removed as soon as possible before they trap sediment and more debris. Partial removal is usually best, once a jam or debris has become established in the stream (Baker 1979; Contreras, Heller, personal communications). A channel allowing water flow should be formed, following the natural stream course as closely as possible. An experienced fisheries biologist should help with the actual operation to prevent further damage from overzealous debris-removal. Anderson (personal communication) has suggested placement of gabions or other suitable structures downstream to collect and retain potential spawning gravels released by debris or jam removal.

Phase removal of debris or jams has also been recommended (Heller, personal communication). A channel is initially made through the jam as described above. The site is rechecked periodically for 2 to 3 years and any materials loosened by the flow or forming a new obstacle to fish passage are removed.

Substantial quantities of fine sediment and debris accumulate behind jams. The amount of sediment released after jam removal is less with partial than with complete removal (Baker 1979). Impact on downstream fish habitat should therefore be less with partial removal. Partial removals also cost less than complete jam removal and require less time to complete (Baker 1979). A tractor usually is the quickest and most efficient method of complete removal (Baker 1979). A tractor should be used when large quantities of buried debris need to be removed. A skyline system is generally more efficient than a tractor in removing large surface logs (Baker 1979). It is less efficient in removing buried logs or small organic debris and is, therefore, more suited to partial removal operations (Baker 1979). Skyline operations also disturb the site less.

The Pacific Northwest Forest and Range Experiment Station of the USDA Forest Service in Juneau, Alaska, is studying immediate effects of debris removal on both physical characteristics of streams and fish populations. Information gained from this project will provide an important evaluation of removal practices and aid fisheries managers with future work.

## Fishways

Fishways are another means of providing access to areas blocked by natural or artificial barriers. The history, description, and specifications of individual fish-passage facilities have been the subject of numerous publications. Clay (1961) and Bell (1973) are good references for fishways, fish screens, and spawning channels, but much of the material is quite detailed. Eicher (1970) provides a succinct overview of fishways and fish passages.

Of the various fish-passage facilities, one general type--the Denil Fishway--has particular significance to forest managers. It is a steep flume with baffles or deflectors on the sides, the bottom, or both. The baffles cause flowing water to deflect back upon itself, thus reducing velocity (and flow). Application to west coast streams was limited until the 1950's, when Ziemer (1962, 1965) began using it experimentally. He tested several modifications for flow velocities and fish passage, species preference at various gradients, and hydraulic considerations. Tests resulted in a portable device known as the Alaskan Steeppass, a unit of 2.8-m (10-ft) sections of aluminum fishway that can be connected to provide relatively steep passage over natural and artificial obstructions (fig. 13). The development of the Alaskan Steeppass has led to many attempts to open new areas for anadromous salmonids--with mixed success. Successful projects in Alaska include the Shrode Lake fishway in Prince William Sound, Navy and Burnett Inlet fishways in southeast Alaska (Sheridan, personal communication), and Billie's Hole fishway on the Chugach National Forest (Roppel 1978 unpubl.).

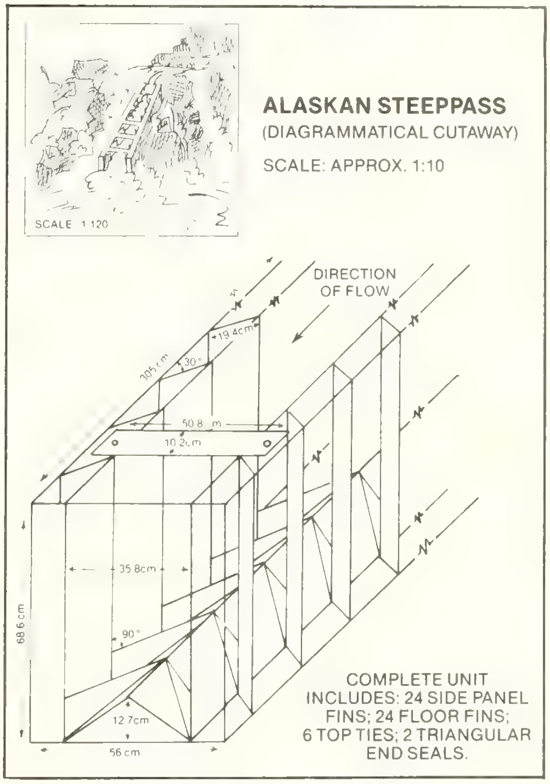


Figure 13.--Alaskan steeppass.

Other steeppass facilities that initially failed to pass fish allowed upstream movement after modifications. The Ketchikan Creek fishway, originally constructed in 1965, passed 300 to 400 pink salmon annually. The structure was rebuilt in 1977 and 10,000 fish migrated above the falls (Roppel 1978 unpubl.). Low flows limited upstream movement through the Gretchen Creek steeppass on Afognak Island, Alaska. A 40-foot, concrete-faced gabion deflector was constructed above the steeppass to raise and divert water through it (Fisher 1973 unpubl.), allowing fish to move upstream at all flows (McDaniel 1978 unpubl.). Such a diversion also reduces mortality of out-migrating fry (Thompson 1975 unpubl.). A gabion wall was also installed to divert high flows at the Pauls and Laura Lakes steeppasses on Afognak Island, Alaska (McDaniel 1978 unpubl.). Construction of a steeppass provided coho salmon and steelhead trout access to Explorer Creek 155, a Vincent Creek tributary in western Oregon (Anderson 1974). The stream had been blocked for 15 years by an improperly placed culvert.

Failures of fishways to pass fish have also been recorded. Poor engineering design and a reduced fish stock contributed to the failure of the Falls Creek fishway in southeast Alaska (Vaughn, personal communication). A steeppass on Luck Creek in southeast Alaska sustained heavy ice damage but was not rebuilt because of low passage of sockeye salmon (Pease 1978a unpubl.). Annual escapement of pink salmon did not increase after a fishway was installed on Portage River, Alaska (McDaniel 1978 unpubl.). At Seal Bay Creek, on Afognak Island, Alaska, pink salmon passage was inadequate to extend spawning naturally to upstream areas (Blackett, personal communication). A steeppass designed to two-thirds scale was installed on Goods Creek, in northern California (Brouha, personal communication). Debris clogging has been a problem, and fish-passage success is unknown.

Opinions differed among engineers and biologists on the final design of the Survey Creek steeppass, on Kosciusko Island, Alaska. Topics of controversy included the lack of intermediate resting pools and the length and slope of the structure (Pease 1978b unpubl.). Biologists believed that the natural stock of fish probably had no genetic impetus to force them through the steeppass, and they questioned the amount and quality of fish habitat above the barrier falls. Nevertheless, the steeppass was constructed--at a cost of $93,000--but no fish have moved upstream (Pease 1978b unpubl.).

Only two of twenty fishways built in British Columbia since 1954 have not justified their cost (Canada Department of Fisheries and the Environment, Fisheries and Marine Service 1978). In Alaska, where most of the United States work has been done, "The benefit/cost ratio for fishways completed to date has varied from 2.0:1 to 30.0:1" (Sheridan 1978 unpubl.). Considering the failures already mentioned, this statement must apply only to successful projects.

Preconstruction benefit/cost ratios are estimated by the method described by Sheridan (1969 unpubl.). No followup evaluations have been made to determine the accuracy of the predicted ratios, nor were the number of fish expected compared to the number actually produced (Sheridan, personal communication). A study should be conducted to determine the validity of the Sheridan (1969 unpubl.) projections for future work.

## Modifying Falls

Falls have been modified by blasting, creating jump pools, or both to improve access. Sweet (1975 unpubl.) listed ten such projects in Alaska. Undoubtedly, similar efforts have been made elsewhere, but documentation and evaluation are lacking. Falls modification projects should not be undertaken without consideration of potential impact on those factors described in the barrier-removal section. Esthetics should be included in project evaluation.

## Culverts

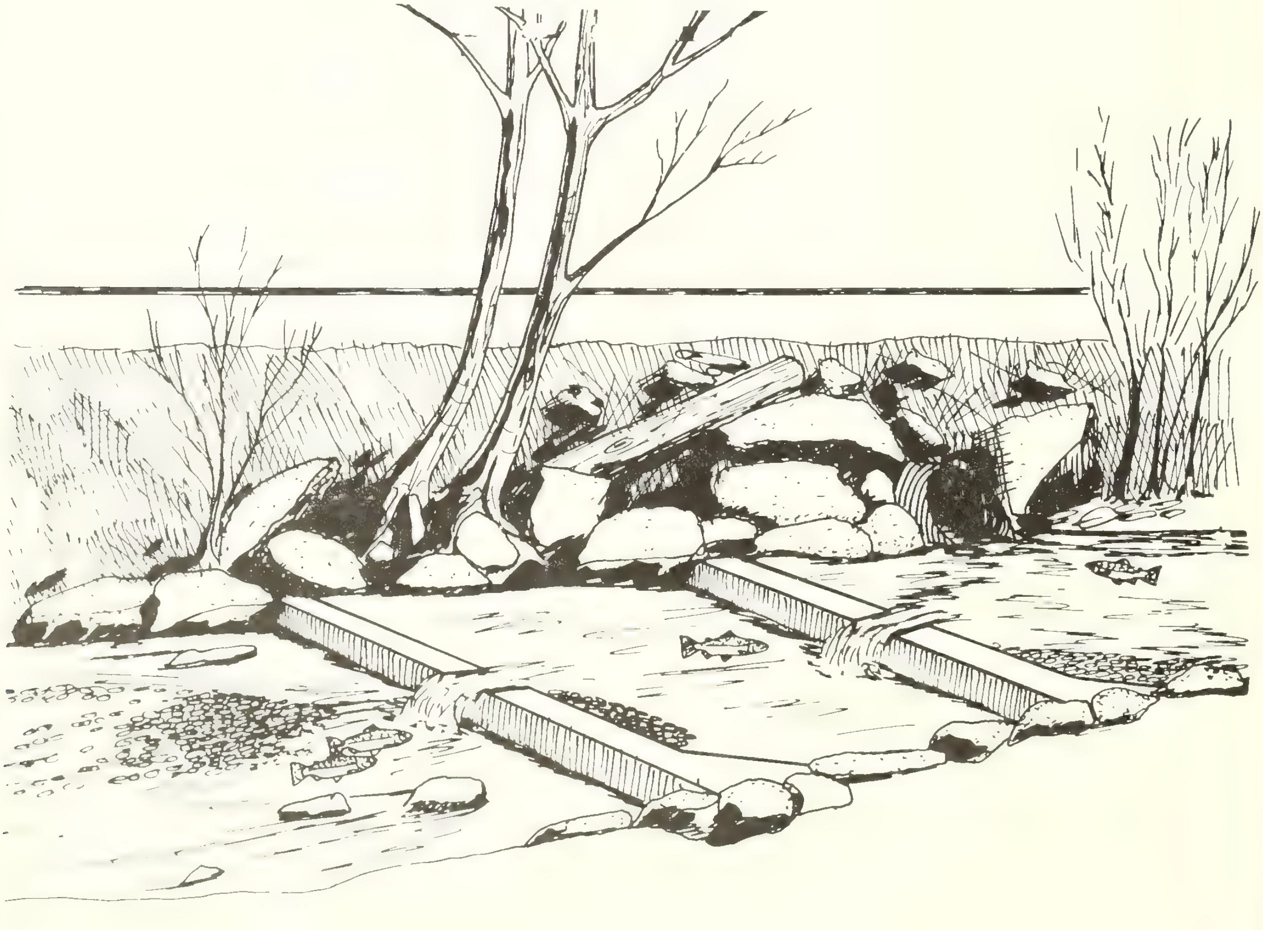
Improperly installed culverts create access problems for both adult and juvenile fish. Fish passage can be impeded by excessive water velocity, inadequate water depth, excessive height of the entrance vertical drop, and lack of adequate resting pools (Alvarado 1978 unpubl.). Reviews of culvert types and fish-passage problems associated with each type have been published (U.S. Department of Agriculture, Forest Service 1977b unpubl.; Dane 1978 a, b). Most culvert designs or culvert modifications have emphasized the upstream passage of adult salmonids. Seasonal upstream movements of juvenile salmonids may occur during the fall (Skeesick 1970, Everest 1973); these small fish require lower water velocities in culverts for successful passage.

Replacement may be the best approach when a culvert hinders or blocks upstream access. In southeast Alaska, an enlarged culvert (30-46 cm larger in diameter than necessary to carry a 25-year storm flow) is partially buried 15-30 cm into the streambed (U.S. Department of Agriculture, Forest Service 1977b unpubl.). This reduces the slope of the culvert and allows bedload sediments to accumulate in it. Bedload deposition decreases "the water velocity in the pipe and provides an irregular texture creating dart and rest areas for small fish" (U.S. Department of Agriculture, Forest Service 1977b unpubl.). A plunge pool (such as is formed by a gabion, piling, or walls) is often created at the culvert outlet (U.S. Department of Agriculture, Forest Service 1977b unpubl.). This increases the end area of the channel, thus dissipating the energy of the flowing water as it runs into the slow-moving water in the pool.

Log and gabion weirs have sometimes been installed to alleviate passage problems resulting from poor culvert installation (Anderson 1973; Evans and Johnston 1980; Brouha, personal communication) (fig. 14). Series of self-scouring log structures (Alvarado 1978 unpubl.) installed in eastern Oregon streams successfully allowed anadromous fish to move through previously impassable culverts (Claire 1978c unpubl.). An unforeseen benefit from these structures was deposition of gravel behind the logs, where resident salmonids have spawned (Claire, personal communication). The pools created by these structures contained up to five times more fish than adjacent areas without structures (Claire 1978c unpubl.).

A program known as "Operation Swim-up" was initiated by the USDA Forest Service in California in 1975 to correct all fish-passage problems on National Forest lands in California within 5 years (Evans, personal communication). Over 3,000 crossing structures have been inventoried, and 300 to 350 of them were identified as barriers to fish passage. Corrective measures have been or are being made to alleviate the problems.

Figure 14.--Weir construction used by Coos Bay, Oregon, District BLM and Oregon State Game Commission to improve fish passage (Anderson 1973).



Baffles were used to produce pockets of low water-velocity where fish could rest when moving through a culvert (U.S. Department of Agriculture, Forest Service 1977b unpubl.; Katopodis et al. 1978). Several types of baffle were evaluated during this study. Prototypes of a new baffle design, made from 0.64-cm (0.25-in) thick steel are currently being field-tested (Brouha, personal communication). These structures could be molded in forms--with a bottom appropriate to the diameter of the culvert--from ferro-concrete or another substance of high strength. The culvert could be dewatered, the surface prepared, and the molded "bumps" glued to the culvert with epoxy adhesive.

## Placing of Boulders

Boulders were placed to create pools providing steelhead trout access into Clearwater Creek, a Smith River tributary in western Oregon previously inaccessible because of its steep gradient (Cameron, personal communication). Fish moved into the creek the spawning season after completion. Installation of cedar-board structures (discussed previously) has contributed to the success of this project.

Boulders were placed above the culvert headwall on Crane Creek, another Smith River tributary (Cameron, personal communication). The boulders not only slow water entering the culvert, but also trap gravel and create resting pools for migrating salmonids.

## Role of the Fishery Biologist

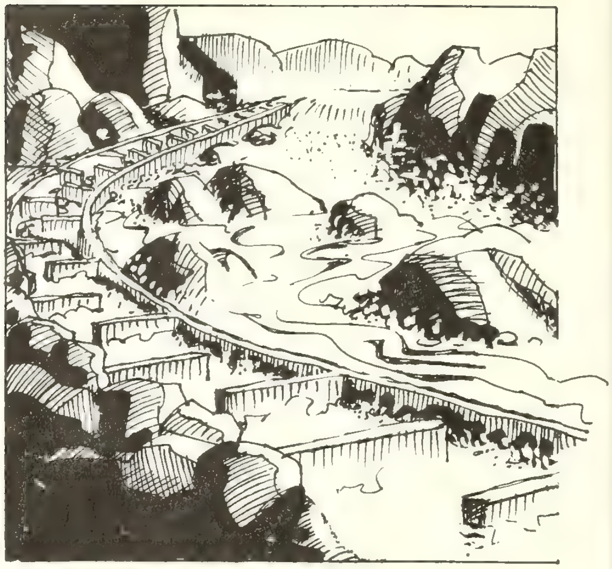
The unique biological and engineering requirements of each access project, as well as insufficient evaluation of past efforts, make general guidelines for developing access projects impossible. Often, initial efforts failed and modification or replacement was required to allow passage. A fisheries biologist must help with the planning to ensure that biological requirements of fish populations are considered in the project design.

## Procedures for Investigating Fish Access

Important procedures (modified from U.S. Department of Agriculture, Forest Service 1977b unpubl.) for improving access are:

- Make certain all planned structures or barrier removals are evaluated by a fishery biologist early in the planning process.
- Determine if fish passage is required and for what species; make a stream survey if necessary.
- Determine periods of year that fish passage is required.
- With assistance from a forest hydrologist, define for structures the maximum flow equaled or exceeded 10 percent of the time, if the fish passage occurs October through April, or 5 percent for the entire year. Also, record minimum flows for which fish passage should be provided. Data can be obtained from U.S. Geological Survey (USGS) records or from precipitation records and converted to cubic feet per second from charts.
- Supply the above information in writing to the forest engineer with a request for an opportunity to review and approve design plans.

- Review the type, size, and slope of structure recommended by the engineer to meet flood requirements. USGS procedures are available for estimating flow on ungaged streams, using regional relations between precipitation and drainage area.
- Have the proposal examined jointly by the biologist and the engineer to determine if adequate fish passage is provided. If fish passage will be impeded, develop alternative designs.
- When a suitable design has been agreed upon for fish passage, have the engineer double check that adequate provisions for flood flow requirements have been made.
- Have the biologist indicate in writing to the engineer that the proposed design plan meets fisheries requirements.
- Have the engineer and the biologist review and approve preliminary design drawings as related to fish passage.
- Submit written recommendations for any special considerations for soil-erosion control at the site during and after construction, as determined jointly by the biologist and the engineer.



# CONCLUSIONS

Assessing current projects to rehabilitate and enhance anadromous salmonid habitat in the Pacific Northwest and Alaska has been difficult. Few projects have been evaluated; many have not even been documented. One person we interviewed thought our efforts would be less than successful because the kind of information we sought was only available from experienced fisheries biologists and managers and just locating these people would require a major effort. Another person said people are more interested in carrying out projects than evaluating them. Both of these statements proved to be accurate.

Few assessments are made because proper studies are costly and time-consuming (White 1975). Several years may be required for optimum habitat conditions to develop after restoration or enhancement, and fish populations may not respond fully for several more years (Hunt 1976). Large fluctuations in populations of anadromous salmonids occur naturally, so detecting change is difficult (Larkin 1974, White 1975).

Most fisheries managers agree that rehabilitation and enhancement projects should be evaluated whenever possible. Limited funds and personnel, however, often preclude postproject evaluation. Managers are often required to improve or restore a certain amount of habitat, and they are unable to give adequate consideration to results. Many managers believe that research organizations, including universities, should develop and evaluate techniques for rehabilitation and enhancement and that these agencies presently fail to meet this need.

Researchers, on the other hand, reported that managers fail to define their research needs, so investigations frequently do not take the direction most beneficial to managers.

Our intention is not to judge the merits of either position. Communication between the two groups is clearly less than adequate. Better rapport must develop between research and management agencies to promote successful rehabilitation and enhancement.

Inconsistent information also made this review difficult. Some written reports implied successful projects, but responsible personnel indicated that results were really less impressive than they appeared on paper. Sometimes we found conflicting assessments of a project.

Valuable information can be gained from past failures; knowing, for example, how various techniques evolved and how similar problems can be prevented in the future would be useful. We cite few failures in this paper because they are often not reported or are less willingly discussed or exhibited than are successful projects.

The knowledge and experience of the biologist generally determines the success of a rehabilitation or enhancement project. The most successful individuals believe that available techniques and methods (with adaptations and modifications to meet the requirements of a specific situation) are adequate. They believe that better enforcement of existing laws and regulations to protect undamaged areas will make more money and energy available for restoration and improvement of degraded and marginal habitats.

Others also desire better enforcement for protecting habitat, but believe that current technology is inadequate to meet the rigorous conditions of most west coast streams. They are therefore reluctant to undertake many restoration or improvement projects.

The Sikes Act (Public Law 93-452) provides funds for projects to improve habitat for fish (and wildlife) on National Forest lands. Projects covered by this act are being planned and conducted in California (Evans et al. 1975) and Alaska (U.S. Department of Agriculture, Forest Service 1976 unpubl.). Additionally, the Forest Management Act of 1976 allows KV (Knutson-Vandenberg Act) funds to be used for forest habitat management, including stream rehabilitation.

Economic analysis is an important tool for comparing various habitat improvement options and estimating benefits and costs of individual projects. Among the important criteria for evaluation are initial and maintenance costs and economic benefits, all discounted over the projected life of the project to provide comparable benefit/cost ratios. Inherent within individual projects are such considerations as life-history patterns and habitat requirements of the affected species, as well as other biological factors. Part of any economic analysis should also be evaluating alternative methods of achieving goals.

Ecological information is also essential to planning. Habitat improvement may sometimes be based on the desires of anglers rather than on requirements of the fish (Hunt 1978). Habitat-improvement projects are directed at only one species of fish, generally the "preferred" fish in a region. All fish species and stocks present should be considered, or adverse side effects may result. Narver (1976) presented an excellent example. In British Columbia, enhancement of a sockeye salmon run was so successful that increased commercial harvesting of sockeye could deplete other stocks of fish that migrate along with them, including the valuable steelhead trout.

When habitat-improvement projects are planned, seasonal and age-specific habitat requirements of target species should be evaluated. Habitat requirements for an individual species may change significantly during the year, particularly between summer and winter (Chapman 1966; Bustard and Narver 1975a, b; Narver 1976). Preferred habitat may also change as fish grow (Mundie 1974, Bustard and Narver 1975a). For example, habitat improvement may be directed at increasing spawning potential, but any increase in production of fry will be negated if rearing habitat or winter cover is not available. Unfortunately, identifying the factors that limit a specific fish population is often difficult. Enhancement projects should therefore be directed at several different habitat requirements, rather than just one.

Finally, potential adverse impacts of stream improvement and rehabilitation work must be considered. Stream hydraulics, hydrology, and geomorphology must be evaluated before any in-stream work is undertaken (Apman and Otis 1965, Heede 1980). Early recognition of the importance of this point by Mackin (1948) seems worthy of reemphasis:

> In connection with control of rivers by men, a safe general implication is that the engineer who alters natural equilibrium relations by diversion or damming or channel-improvement measures will often find that he has a bull by the tail and is unable to let go--as he continues to correct or suppress undesirable phases of the chain reaction of the stream to the initial "stress" he will necessarily place increasing emphasis on study of the genetic aspects of the equilibrium in order that he may work with rivers, rather than merely on them. It is certain that the long-term response of streams to the operations of the present generation of engineers will provide much employment for future generations of engineers and lawyers.

When a barrier to anadromous fish is removed, how might resident fish populations above the barrier be affected? How will fish passage structures such as a ladder or steeppass affect esthetic values? "Improvement" projects may create unanticipated side effects, both favorable and unfavorable. Stream-improvement plans should be evaluated not only in terms of the proposed benefit, but also with thought to potential adverse impacts.

Proposed projects should be considered for streams, watersheds, and whole regions. Biologists have often been concerned more with mitigating past problems than with preventing future ones; an example is the seeding of landslides. Several problems in aquatic habitats are associated entirely with processes and management activities well upslope from anadromous stream channels, such as the relation between log-debris jams and debris torrents initiated by management activities. In some unstable headwater streams, habitat protection can be accomplished only by controlling timber harvesting activities and using specific yarding systems and debris-management policies. Although few fishery biologists have experience in related fields such as forestry, soils, and geology, most are associated with personnel who have expertise in these disciplines. Protection of anadromous fish habitat must be an interdisciplinary activity.

As Hynes (1975) stated, "We must...not divorce the stream from its valley." We must recognize riparian disturbances and hillslope processes as an integral part of habitat management. Intelligent management of all resources within a basin is the key to maintaining stream systems that are characterized by productive habitats (Richards 1964).

## SUMMARY

Protection of the habitat should be the primary goal of resource managers concerned with sustaining fishery yields (Powers 1973). Habitat rehabilitation and enhancement, however, have shown promising results in many areas of the Pacific Northwest, despite the lack of documented successes. Available techniques and methods, with modifications as required, can increase natural salmonid production in marginal and degraded areas and help meet the demand for wild anadromous fishes. Simple and obvious techniques are most likely to be the safest because they offer the least opportunity for adverse side effects (Larkin 1974).

We need to adopt an experimental approach of learning as we go, to refine present methods and develop new ones. Small-scale projects with evaluations should be initiated in different areas so that local requirements are met. Project results should be evaluated and the results--both successes and failures--must be readily available. The experimental approach demands "the integration of the distinctive and complementary roles of managers and researchers in careful design of plan, execution, and assessment for each major project" (Loftus 1976). This integration may pose the greatest challenge in advancing the art of rehabilitating and enhancing habitat for anadromous salmonids.

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# DIRECTORY FOR PERSONAL COMMUNICATIONS

Anderson, J. W. (1978)
USDI Bureau of Land Management
333 South Fourth
Coos Bay, OR 97420

Andrews, J. L. (1981)
USDA Forest Service
Umatilla National Forest
2517 S. W. Hailey Avenue
Pendleton, OR 97801

Barnes, J. (1978)
USDA Forest Service
Six Rivers National Forest
610 F Street
Eureka, CA 95501

Bender, R.; Mullarkey, W. (1978)
Oregon Department of Fish
and Wildlife
300 Fifth Street, Bay Park
Coos Bay, OR 97420

Blackett, R. (1978)
Alaska Department of Fish and Game
F.R.E.D. Division
P.O. Box 686
Kodiak, AK 99615

Brouha, P. (1978)
USDA Forest Service
Shasta-Trinity National Forest
2400 Washington Street
Redding, CA 96001

Cameron, J. (1978)
USDI Bureau of Land Management
333 South Fourth
Coos Bay, OR 97420

laire, E. (1978)
Oregon Department of Fish
and Wildlife
P.O. Box 19
John Day, OR 97845

ontreras, G. P. (1978)
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Sawtooth National Recreation Area
Star Route
Ketchum, ID 83340

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Washington State Department
of Fisheries
115 General Administration Building
Olympia, WA 98504

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USDA Forest Service
630 Sansome Street
San Francisco, CA 94111

Everest, F. H. (1978)
USDA Forest Service
Forestry Sciences Laboratory
3200 Jefferson Way
Corvallis, OR 97331

Hammer, R. (1978)
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Eugene District Office
1225 Pearl Street
Eugene, OR 97401

Heller, D. (1978)
USDA Forest Service
Mt. Hood National Forest
19559 Division
Portland, OR 97030

Hutchison, J. (1978)
Oregon Department of Fish
and Wildlife
Route 5, Box 325
Corvallis, OR 97330

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Bureau of Reclamation
Sacramento, CA 95825

Marriott, D. M. (1978)
California Department of Fish
and Game
627 Cypress
Redding, CA 96001

Narver, D. W. (1978)
British Columbia Ministry of
the Environment
Fish and Wildlife Branch
400-1019 Wharf Street
Victoria, BC V8W 2Z1

Newton, J. (1978)
Oregon Department of Fish and Wildlife
3701 West 13th
The Dalles, OR 97058

Platts, W. C. (1978)
USDA Forest Service
Intermountain Forest and Range Experiment Station
316 East Myrtle
Boise, ID 83706

Sheridan, W. L. (1978)
USDA Forest Service
P.O. Box 1628
Juneau, AK 99802

Slaney, P. A. (1978)
British Columbia Ministry of the Environment
Fish and Wildlife Branch
Vancouver, BC V6T 1W5

Vaughn, J. (1978)
Alaska Department of Fish and Game
F.R.E.D. Division
Subport Building
Juneau, AK 99801

Wilson, D. A. (1978)
Washington State Department of Fisheries
115 General Administration Building
Olympia, WA 98504

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Agriculture

**Forest Service**

Pacific Northwest
Forest and Range
Experiment Station

General Technical
Report
PNW-141

August 1982

# Sediment Budgets and Routing in Forested Drainage Basins

Frederick J. Swanson, Richard J. Janda,
Thomas Dunne, and Douglas N. Swanston

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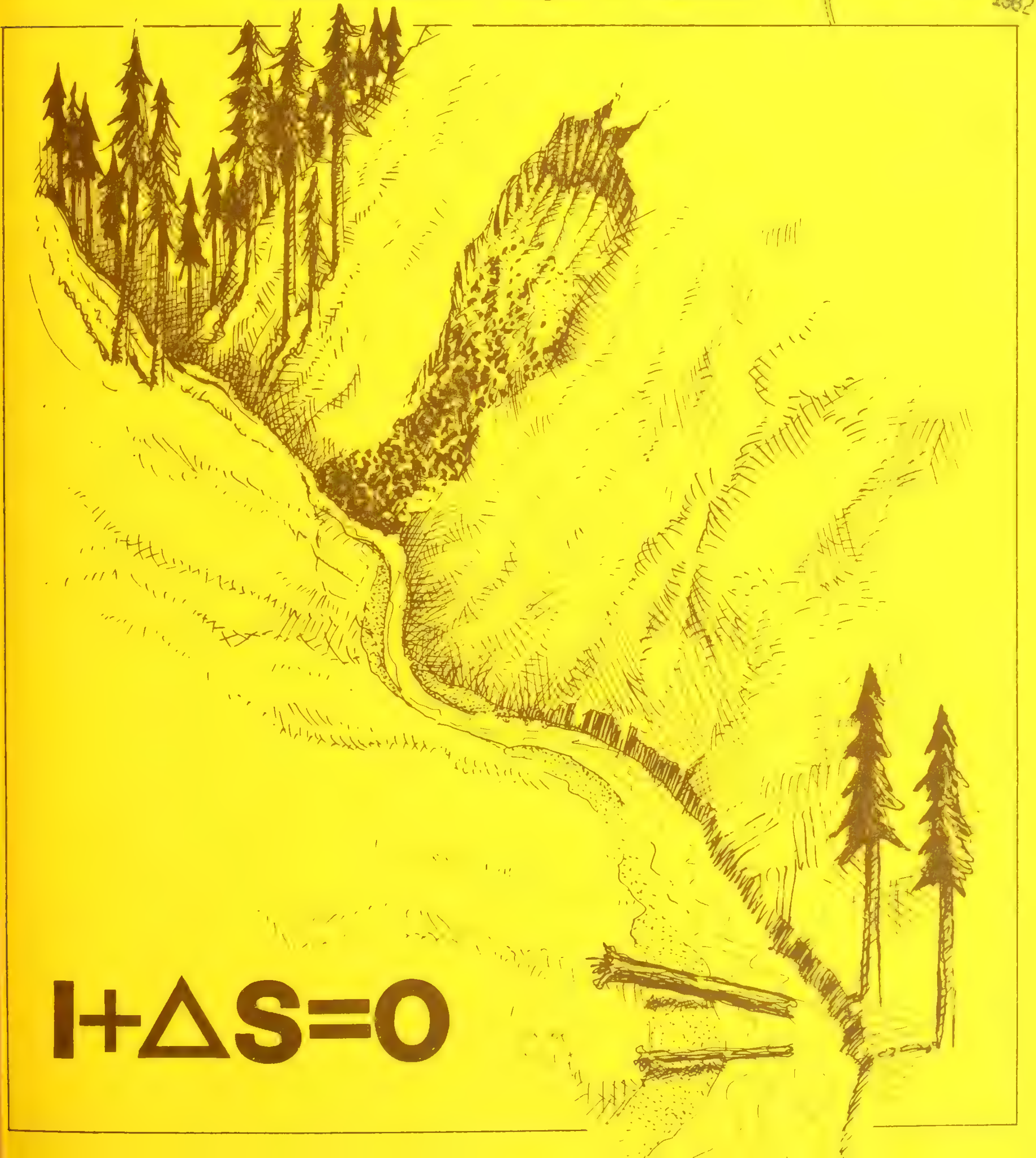

## METRIC EQUIVALENTS

1 millimeter (mm) = 0.039 inches
1 centimeter (cm) = 0.39 inches
1 meter (m) = 1.09 yards
1 kilometer (km) = 0.62 miles
1 hectare (ha) = 2.47 acres
1 square kilometer (km$^2$) = 0.39 square miles
1 cubic meter (m$^3$) = 1.31 cubic yards
1 cubic meter per meter (m$^3$/m) = 1.20 cubic yards per yard
1 cubic meter per hectare (m$^3$/ha) = 0.53 cubic yard per acre
1 kilogram (kg) = 2.20 pounds
1 metric tonne (t) = 1.10 English tons
1 tonne per hectare (t/ha) = 0.45 ton per acre
1 tonne per square kilometer (t/km$^2$) = 2.82 tons per square mile
1 tonne per cubic meter (t/m$^3$) = 0.84 ton per cubic yard
1 liter per second (L/sec) = 0.035 cubic feet per second
1 cubic meter per second (m$^3$/sec) = 35.3 cubic feet per second
1 dyne per square centimeter (dy/cm$^2$) = 1.45 x 10$^{-5}$ pound weight per square inch

# ABSTRACT

Swanson, Frederick J.; Janda, Richard J.; Dunne, Thomas; Swanston, Douglas N., tech. eds. Workshop on sediment budgets and routing in forested drainage basins: proceedings. Gen. Tech. Rep. PNW-141. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 165 p.

Sediment budgets quantify the transport and storage of soil and sediment in drainage basins or smaller landscape units. Studies of sediment routing deal with the overall movement of soil and sediment through a series of landscape units. The 14 papers and 5 summaries from discussion groups in this volume report results of sediment budget and routing studies conducted principally in forested drainage basins. Papers also deal with sediment routing studies using computer models, physical models, and field observations in nonforest environments.

This work emphasizes methods for judging the relative importance of sediment sources within a basin, the many roles of biological factors in sediment transport and storage, and the importance of recognizing changes of sediment storage within basins when interpreting sediment yield. Sediment budget and routing studies are important tools for both research scientists and land managers.

Keywords: Sedimentation, watershed management, sediment budget, drainage basins, geomorphology.

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# Introduction: Workshop on Sediment Budgets and Routing in Forested Drainage Basins

Frederick J. Swanson, Richard J. Janda, Thomas Dunne, and
Douglas N. Swanston

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ederick J. Swanson, Research Geologist, Forestry
iences Laboratory, 3200 Jefferson Way,
rvallis, Oregon 97331; ; Richard J. Janda,
search Geologist, Water Resources Division, U.S.
partment of Interior, Geological Survey,
ncouver, Washington 98661; Thomas Dunne,
ofessor, Department of Geological Sciences,
iversity of Washington, Seattle, Washington
195; Douglas N. Swanston, Principal Geologist,
restry Sciences Laboratory, P.O. Box 909,
neau, Alaska 99802.

Geomorphologists have traditionally studied erosion of landscapes by analysis of individual erosion processes, measurement of sediment yield at one or more points along a river system, and stratigraphic analysis of deposits. These approaches, however, have rarely been used collectively to provide a framework for understanding soil and sediment movement through drainage basins. Many current problems in basic and applied geomorphology and ecology can be better addressed when placed in the broad, conceptual framework provided by analysis of sediment budgets and routing. Such analysis provides an understanding of geomorphic systems, just as similar studies have been fruitful in analysis of nutrient cycling, hydrology, and other complex systems.

Movement of soil and sediment through drainage basins commences with sediment production from bedrock weathering augmented by dust input from the atmosphere and biological production of organic matter. The organic and inorganic components of soil and sediment move down hillslopes by a great variety of processes, some operating more or less continuously but others only seasonally or episodically. Movement may occur by a sequence of linked processes or by several independent processes acting simultaneously. Soil eventually enters stream channels where it is subject to transport by fluvial processes. Between periods of movement, soil and sediment are temporarily stored at a variety of sites. They may undergo chemical and physical change while in storage and during transport. Both movement and storage are strongly influenced by live and dead vegetation.

A sediment budget is a quantitative description of this movement of sediment through a single landscape unit. Here, sediment refers to erodible materials at or near the earth's surface, including both organic and inorganic matter on hillslopes and in channels. A complete budget considers input rate, storage volume, type of modification, and discharge rate of sediment. The landscape unit may be an entire drainage basin, a hillslope segment, a first-order stream channel, or other feature. For example, the sediment budget of a first-order stream channel may include measurement of material transport across the channel margins by hillslope processes, changes in storage, and total sediment discharge from the channel.

The term "sediment routing" is used both generally and specifically. Many investigators, including most of those in this volume, use the term in a nonquantitative sense to convey the concept of sediment movement through a drainage basin. Parallel to use of the term "flood routing," sediment routing, in a stricter sense, is the computation of the movement of sediment through a series of landscape units and of the modification of the sediment during its passage. The computation is based on the continuity equation for sediment transport through successive landscape units along the flow path. Output from one landscape unit becomes input to the next unit downslope or downstream. Thus, if the conveyance of sediment through a first-order channel is of interest, the channel might be divided into increments, and input, output, and change in storage of each size fraction in each increment would be observed. Input would include transport from upstream as well as transport across the channel margins. How well a budget and routing procedure characterizes and quantifies a geomorphic system depends on how well transfers, storages, and linkages in the system are understood; the precision and duration of field measurements; and the scale of spatial and temporal segmentation of the drainage basin under analysis.

Sediment transport and storage constrain development, structure, and composition of terrestrial and aquatic ecosystems. Conversely, vegetation and, to some extent, fauna influence sediment routing in most landscapes by affecting sediment transport and storage and by directly contributing an important organic component to the total sediment load.

Several features distinguish sediment routing in forest environments from that in other vegetation types. Forest vegetation plays a prominent role in many phases of sediment transport and storage. Transport of soil by windthrow of trees, the binding of soil by tree roots, and other vegetative factors affect soil movement in forests. Standing trees and fallen logs on hillslopes and in channels trap and store sediment temporarily. Sediment-routing systems are influenced by forest-managememt activities, including road construction and removal of vegetation. Short-term studies of sediment routing in forested drainage basins should be put in the context of vegetative succession on this time scale; changes in forest plant communities that directly control sediment routing typically occur over a period of several decades to a century or more after severe disturbances. On a longer time scale, evaluation of management impacts on sedimentation should consider the frequency and erosional consequences of disturbances of soil and vegetation by human activities, as well as natural forest disturbances such as wildfire and windthrow.

Sediment-routing studies and budgets have been used for a variety of purposes. Early studies centered on the basic problem of how sediment moves through landscapes. Even within these basic studies, different areas have been emphasized. Dietrich and Dunne (1978), for example, were particularly interested in changes in properties of soil and sediment moving through drainage basins, and they analyzed sediment transport from the long-term perspective of sedimentary petrology and steady-state geomorphology. Rapp (1960) and Caine (1976), on the other hand, were more concerned with the relative importance of high magnitude, episodic events and low magnitude, more frequent or continuous processes. Leopold et al. (1966) measured rates of slope and channel processes in a semiarid area to aid analysis of arroyo filling and cutting. Swanson et al. (1982) developed a sediment budget to analyze the relative importance of physical processes in the transport of organic and inorganic matter through a steep, forested drainage basin and compared this budget with one for a less steep drainage basin forested with a younger stand.

Sediment-budget studies have also been useful in analyzing effects of management practices on soil erosion, sediment yield, and water quality. Kelsey (1977) and Lehre (1980) observed that land use altered the relative importance of some storage sites and transfer processes in sediment-routing systems in northern California. Fredriksen (1970), Janda (1978), and others have analyzed partial sediment budgets with the specific purpose of interpreting sediment contributions from human-influenced sources in forest environments. Consideration of sediment-routing concepts can also help managers design effective networks for monitoring management impacts on soil, stream channels, and water quality.

The diversity of objectives, approaches, and professional disciplines of those who conduct sediment-routing and budget studies in forest environments has resulted in poor communication among scientists and land managers with this common interest. To encourage communication and a useful commonality of approaches, we convened a workshop on Sediment Budgets and Routing in Forest Drainage Basins on May 30 through June 2, 1979, at the Forestry Sciences Laboratory, Corvallis, Oregon. The workshop was cosponsored by the National Science Foundation and the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service. The workshop format provided for roughly equal division between formal talks and small group discussions. Participants were encouraged to emphasize theory and to speculate on new approaches in study design and problem analysis.

This volume contains papers presented at the workshop and summaries of some discussion groups. Some papers do not deal explicitly with forest environments but are included because they offer principles or techniques useful to sediment-routing and budget studies. The papers are grouped into those dealing with general issues in sediment-routing and budgets and those dealing with case studies of sediment movement and storage on hillslopes and in channels. First, Dietrich, Dunn, Humphrey, and Reid suggest basic rules for developing a sediment budget with examples from forested areas of the Pacific Northwest. Simons, Li, Ward, and Shiao follow with a paper discussing computer-simulation modeling, as both a tool for understanding general characteristics of sediment-routing systems and for predicting impacts of some management activities. Using examples from steep, chaparral-covered basins, Rice examines difficulties in modeling sediment routing in landscapes that are greatly modified by randomly occurring, extreme, and infrequent events. Vegetation-free sediment-routing systems of badland environments and laboratory models provide opportunity to examine some general, systematic patterns of sediment routing as described by Harvey and Bergstrom.

Two case studies deal primarily with slope processes. Lehre presents a sediment budget that emphasizes slope processes in a small drainage basin in the central California coast. Hupp and Sigafoos describe use of dendrochronologic methods to assess slope processes on block fields in the Appalachian Mountains.

Papers by Kelsey, Madej, Taylor, and Smith and Hicks address sediment transport along stream channels and interpret transport characteristics in terms of sediment supply by hillslope processes.

Two papers analyze the characteristics of large woody debris in streams as they affect sediment storage. Megahan's studies of channel storage in small streams in the Idaho Batholith concern the effects of forest-management practices on channel stability and sediment yield. Likens and Bilby use examples from the White Mountains in central New Hampshire to describe the evolution of organic-debris dams in relation to forest stand development.

In the final paper, Swanson and Fredriksen discuss application of sediment-routing and budget concepts to analysis of erosional consequences of forest management.

Five brief reports of discussion sections follow the formal papers. Groups of 7 to 16 participants met in afternoon sessions for informal discussions of identifying and mapping sources and storage areas of sediment; tracing and dating the movement and storage of sediment; the role of weathering and soil formation in sediment routing; the influence of magnitude, frequency, and persistence of various types of disturbance on geomorphic form and process; and the use of flowcharts in sediment-routing studies. These discussions provided scientists of diverse backgrounds opportunity to exchange ideas and concerns, to identify unresolved problems, and to focus on future research needs. These discussions did not result in consensus or state-of-the-art statements for each topic because of time limitations, the broad scope of each topic, and our limited knowledge and techniques for addressing the problems. Lack of common definitions of processes and storages and common measurement techniques frustrated some attempts to compare geomorphic systems in different physiographic and ecologic settings.

Readers of this volume may become aware of several recurring themes: interactions between vegetation and sedimentation systems are numerous and complex; forest vegetation makes these environments highly retentive of sediment; and sediment-routing studies provide a useful approach to holistic analysis of drainage-basin function. These issues, along with identified research needs, are discussed more fully in a concluding statement. Analysis of sediment budgets and routing offers great promise in study of drainage-basin evolution and impacts of management practices on sedimentation and on forest and stream ecosystems.

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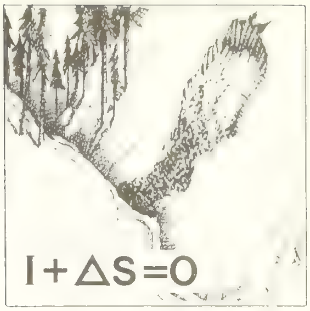

# Papers

## Construction of Sediment Budgets for Drainage Basins

William E. Dietrich, Thomas Dunne, Neil F. Humphrey, and
Leslie M. Reid

ABSTRACT

A sediment budget for a drainage basin is a quantitative statement of the rates of production, transport, and discharge of detritus. To construct a sediment budget for a drainage basin, one must integrate the temporal and spatial variations of transport and storage processes. This requires: recognition and quantification of transport processes, recognition and quantification of storage elements, and identification of linkages among transport processes and storage elements. To accomplish this task, it is necessary to know the detailed dynamics of transport processes and storage sites, including such problems as defining the recurrence interval of each transport process at a place.

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William E. Dietrich, Assistant Professor, Department of Geology and Geophysics, University of California, Berkeley, California 94720; Thomas Dunne, Professor; Neil F. Humphrey, Graduate Student, Leslie M. Reid, Graduate Student, Department of Geological Sciences and Quaternary Research Center, University of Washington, Seattle, Washington 98195.

## INTRODUCTION

A sediment budget for a drainage basin is a conceptual simplification of the interaction of processes that convey debris from bedrock down hillslopes and channels and out of the basin. Monitoring the creation and movement of all particles in a drainage basin is impossible, and the recurrence and progress of many processes exceed the lifespan of the researcher. These obstacles force us to develop conceptual models of sediment generation and transfer that can guide field measurements. Such a framework is valuable in decisions about where to take representative measurements, about how to extrapolate data to unmonitored parts of a basin, and about how to measure debris transport.

Definition of sediment budgets has been inhibited by a lack of models for the mechanics of processes, by failure to define processes clearly, and by the great difficulty in measuring rates of sediment transfer. We cannot propose a single general method for construction of a budget. Instead we suggest an essential list of elements that all sediment budgets must have to be meaningful. We begin by proposing a definition of a sediment budget that leads to the requirements in construction of a sediment budget. The rest of the paper is devoted to an examination of these requirements, using as illustrations problems we have encountered in our fieldwork in the coastal mountains of Oregon and Washington. A central theme of this paper is that, with a small, but essential amount of fieldwork, an approximate sediment budget can be constructed that satisfies our suggested requirements and can be used as a guide for a monitoring program.

## DEFINITION OF A SEDIMENT BUDGET

A sediment budget for a drainage basin is a quantitative statement of the rates of production, transport, and discharge of detritus. In most studies, measurement of sediment production is assumed equivalent to quantification of sources of sediment discharged into channels. Sediment is also produced by the chemical degradation and physical mixing of weathered bedrock to form a soil, however, and material is transferred between size fractions as a result of attrition during transport. Also, the rate and nature of sediment production from the bedrock by soil-forming processes may affect significantly the rate of hillslope erosion and mode of fluvial debris transport. In a sediment budget, the soil mantle should be treated as a separate element of sediment storage having a definable rate of inflow and outflow of detritus. Quantification of debris transport requires not only defining rates of sediment transfer between major storage elements--such as between soil and stream channels--but also computing rates of movement through these sediment reservoirs. The latter is particularly difficult to do with present understanding of processes, but it is from such a quantification that predictions can be made about the change in size of storage elements and the rapidity and magnitude of the response of sediment discharge from a drainage basin after some disturbance. Discharge of detritus is simply the rate of transport of sediment past a monitoring station.

To construct a sediment budget for a drainage basin, the temporal and spatial variations of transport and storage processes must be integrated, and to do so, these requirements should b fulfilled: (1) recognition and quantification of transport processes, (2) recognition and quantification of storage elements, and (3) identificatio of linkages among transport processes and storage elements. To accomplish this task, it is necessa to know the detailed dynamics of transport processes and storage sites, including such problems as defining the recurrence interval of each transport process at a place.

## RECOGNITION AND QUANTIFICATION OF TRANSPORT PROCESSES

A careful, long-term monitoring program designed to sample the spatial and temporal variations in elements of a sediment budget is an expensive venture. Such programs have usually been undertaken to answer questions about rates of landform evolution (Rapp 1960), effects of climatic change (Leopold et al. 1966), and effects of land use (Fredriksen 1970, Janda et al. 1975, Swanson, et al. (1982). Yet, as illustrated by Leopold and his associates, a careful examination of the processes is needed both to interpret the results of measurements and to evaluate the effects of changes in the major controls of processes. Construction of predictive sediment budgets is hindered by the lack of understanding of the mechanics of processes. At present, no transport process is sufficiently well understood that field data on major controls can be used to predict transport rates. Until studies of such processes as soil creep, landslides, sheetwash, and sediment transport in river channels produce realistic mathematical models, we must rely on extensive monitoring to provide data on transport rates.

Before a monitoring program is begun, it is essential to recognize and quantify approximately the major processes that generate and transport sediment. An initial field study should be made to identify the distribution of dominant transport processes and interrelationships among them. From such a survey and from currently available theory for the physics of transport processes, a program of monitoring can be established to sample the range in values of major controls and the spatial variation of processes as a function of these controls. The only way to generalize from a few measurement sites to a landscape is to develop predictive models of the relation of each transport process to its controls.

An important step in the simplication of a sediment budget to a form that can be examined in the field is the recognition of the dominant hillslope erosion processes. Striking differences in dominant processes occur in forested areas of different climate, geology, and land use. The dominance of a process can also depend on stand history. A dramatic example is the period of intense rain splash, sheetwash, and dry ravel that occurs after a major burn in the chaparral of Southern California (Rice, this volume). A central issue in this case becomes the assessment of the transport of sediment (on hillslopes, into and along channels) after specific burns, relative to the total transport evaluated over a period sufficiently long to accommodate the spatial and temporal variation in magnitude and intensity of burns. In this paper, we refer to the recognition and measurement of only a few processes that have been shown to be important in wet, forested environments.

### Slumps and Earthflows

In some landscapes underlain by mechanically weak rocks, massive earthflows and slumps move large quantities of debris to channel perimeters where shallow debris slides discharge sediment into the channel (as described by Swanson and Swanston 1977). These deep-seated movements involve soil, saprolite, weathered bedrock, or fresh bedrock and can extend to tens of meters below the soil surface. Engineering geologists who have measured relatively slow rates of movement in these deep-seated features have referred to the movement as creep (e.g., Wilson 1970, Swanston and Swanson 1976). This has clouded the distinction between earthflow and creep. For clarity, here we will refer to slow mass movement of just the soil mantle as soil creep. This distinction matters: measured engineering "creep" tends to be much faster than soil creep and to occur by a different process.

Slumps and earthflows can persist for thousands of years as topographic features and occasional sources of sediment, according to Swanston and Swanson (1976) and Gil and Kotarba (1977), who have begun to investigate the conditions under which this form of hillslope transport occurs. Kelsey (1978) has emphasized that earthflows covering only a small proportion of a basin may provide a major input of sediment to the channel. Therefore, careful mapping of these features is necessary at an early stage of budget studies. This is not an easy task in densely forested regions where the surface expression of the slump-earthflow may be subdued after periods of relatively slow movement. Measurement of the discharge of sediment from earthflows requires drilling and the installation of flexible tubing anchored in a stable substrate. Deformation of the tube is measured with an electrical inclinometer (Kojan 1968, Swanston and Swanson 1976) to provide a vertical profile of velocity. The difficulty and cost of installation limits the number of measurement sites, so that the velocity field is poorly defined. Inclinometer measurements can be augmented by repeated survey of stakes on the surface of the earthflow, however. Even without inclinometer measurements, the discharge can sometimes be adequately defined from data on depths of movement and surface velocities (Gil and Kotarba 1977, Kelsey 1977).

### Debris Slides

The importance of debris slides in forested mountains has been emphasized by Swanston (1969, 1970), O'Loughlin and Pearce (1976), and many others. Such failures typically occur in at least three physiographic locations. On the footslopes of hills, relatively small debris slides convey soil and weathered bedrock into adjacent channels. Much of the soil transported by these debris slides may have been moved to the footslopes from further upslope by soil creep and earthflows. The volume and frequency of this transfer across the hillslope-channel interface must be measured if this component of the sediment budget must be isolated. In some budgets where only the total sediment flux is required, however, it may suffice to assess the sediment transport by other processes on the hillside and to ignore this last step in the transfer to channels (Dietrich and Dunne 1978). Debris slides and avalanches also occur along hillslope profiles and convey all or a portion of displaced sediment to the channel. Again, it is necessary to obtain volume, proportionn reaching the stream, the centroid displacement of the remainder, and the frequency of transport. This may be done through a combination of fieldwork and aerial photographic interpretation (e.g., Simonette 1967). The relatively short aerial photograph record can sometimes be extended by using dendrochronology to date older landslides. Finally, debris slides and debris flows often originate in topographic hollows at stream heads or in thick soils in bedrock hollows, which Dietrich and Dunne(1978) have called "wedges." Their role in the sediment budget must be defined in the same way as slides on planar hillsides.

Increased debris sliding caused by forest clearing and road construction has been examined in many different forests (see Gresswell et al. 1979, for a recent example and for references). Typically, the frequency of debris-sliding increases in the cut areas, and a fourth location for debris slides--the road-affected region--is added to the landscape. Here, distinguishing between debris slides from road fill, cut bank, and channel crossing may be necessary because each may have different volume, distance of travel, frequency of occurrence, and sensitivity to predisturbance conditions and management practices.

### Soil Creep and Biogenic Transport

The term "soil creep" is generally used to refer to a group of processes that result in relatively slow downhill movement of the soil mantle (Young 1971, Carson and Kirkby 1972). These processes include the mass flow of debris under continuous shear stress imposed by the downslope component of the soil weight; displacement of soil by expansion and contraction from wetting and drying or freezing and thawing; expansion, collapse, and settling of debris caused by weathering (Young 1978); and downslope movement by raveling and spalling of surface debris. The relative importance of these processes in the sediment budgets of forested drainage basins is generally unknown because few measurements have been attempted, and no theory exists to predict movement based on soil properties. In environments in which slumping, earthflow, and midslope debris slides are rare or nonexistent and rain splash and overland flow are unimportant, however, the rate of supply of sediment to channels must be controlled by soil creep and the equally subtle processes associated with biogenic transport.

The difficulty of making field measurements of soil creep has prevented quantification of its role in the sediment budget and has impeded the development of predictive models of the processes involved. A simple, accurate method for monitoring soil creep and its controls, which allows rapid installation of a large number of monitoring sites, has not been developed. Further, different processes require different measurement techniques. A review of the various methods that have been used can be found in Young (1971), Carson and Kirkby (1972), and Anderson and Cox (1978). Continued work like the study by Fleming and Johnson (1975) on soil creep in northern California would be valuable in the context of a sediment-budget study. They used flexible tubing to monitor the seasonal rate of creep as controlled by moisture content of the soil. They successfully demonstrated the importance of rate and process theory (Mitchell 1976) to the understanding of the mechanics of soil experiencing mass flow, although they were unable to use the theory quantitatively in its present form. From field measurements and mapping of soils and bedrock, they also examined the geologic and topographic controls of soil movement.

Biogenic transport is the movement of debris as a result of biological activity. Biological activity is the cause of the transport rather than simply a control or influence and can be divided into two categories according to rate. Such processes as tree throw and animal burrowing cause local catastrophic transport, but pervasive processes such as root growth and wind stress on trees result in the slow transport of debris. Biogenic transport has traditionally been subsumed under the term soil creep; it is caused, however, by a set of processes unlike those generating soil creep. Although often mentioned as causes of downslope movement of debris, biogenic transport processes have been the object of only a few careful studies. These include studies of animal burrowing by gophers (Thorn 1978, and articles referred to therein), termites (Williams 1973), voles and moles (Imeson 1976), and by beetles (Yair 1976), as well as studies of tree throw (Denny and Goodlett 1956, Kotarba 1970, and Swanson et al. (1982).

These studies have largely focused on the direct movement of soil by the organism; the annual transport rate is calculated as the product of the volume of soil displaced, distance it has moved, and annual frequency of disturbance on a hillside divided by the area of the hillslope. The distance moved is simply the downslope distance between the centroids of the soil mass in its original and displaced position. This transport rate can only be computed from direct observation of the volume, centroid displacement, and frequency. Traditional creep-monitoring techniques will not detect it.

Displacement of soil by animals is followed by filling of the burrow or hole and the decay of the exposed mound, which may both be caused by abiotic processes. Complete evaluation of biogenic transport should include quantification of these secondary processes. One such study by Imeson (1977) suggests that rain splash of exposed soil mounds formed by voles is an important contributor of sediment to channels in the deciduous forests of Luxembourg.

Although Kirkby (1967) and others have generally considered biogenic transport to be unimportant, recent studies cited above suggest that in some regions it may dominate transport over much of the hillslope. In particular, in some forested landscapes the importance of tree throw is clearly expressed by the microtopography created by decaying tree-throw mounds.

Estimates of tree-throw transport rate in terms of equivalent rate of soil creep also suggest its importance. Denny and Goodlett (1956) computed a transport rate equivalent to 1.5 mm/year in the central Appalachians. Kotarba (1970) found that a single wind storm in the Tatra Mountains of Poland caused transport approximately equivalent to 20 cm of soil creep on some hillslopes (assuming average soil depth to be 50 cm). The trees that fell were on the average about 135 years old, which would give an average soil creep rate of roughly 2 mm/year over the lifespan of the tree as a result of this single storm. In the Olympic Mountains of coastal Washington, we have computed a tree-throw rate of 1.8 mm/year for a roughly 80-year period (Reid 1981). These transport rates are comparable in magnitude to soil-creep measurements in forested hillsides (Barr and Swanston 1970, Eyles and Ho 1970, Lewis 1976); if representative, they strongly suggest the need to incorporate tree-throw transport into hillslope sediment budgets.

### Sheetwash and Rain Splash

Sheetwash and rain splash are relatively ineffective in transporting sediment in undisturbed forested basins in the Pacific Northwest. The high soil permeability and thick humus layer confine such activity to areas of recent disturbance--such as landslide scars, rootwads, tree-throw scars, and areas of bank erosion--all of which are soon revegetated. In logged basins, however, these processes take on a new significance. Not only is the area laid bare by landslides and bank erosion increased, but new forms of disturbance such as road building, log yarding, and slash-burning expose even larger areas of mineral soil. On skid trails and slash-burn surfaces, infiltration capacities often remain high enough that overland flow does not occur; but gravel road surfaces are well compacted, their permeabilities are lowered, and sheetwash is frequency generated.

The contribution of sediment to streams from surface erosion from roads can be added as a separate element to the sediment budget. For a sediment budget to be of value for management decisions, it should include an evaluation of the role of road design and usage on sediment yield. Unlike for many of the processes described above, quantitative predictions can now be made of rates of sediment transport from roads based on simple field measurement of major controls. For example, in a study of the effects of roads on the sediment discharge into streams of the Clearwater basins in

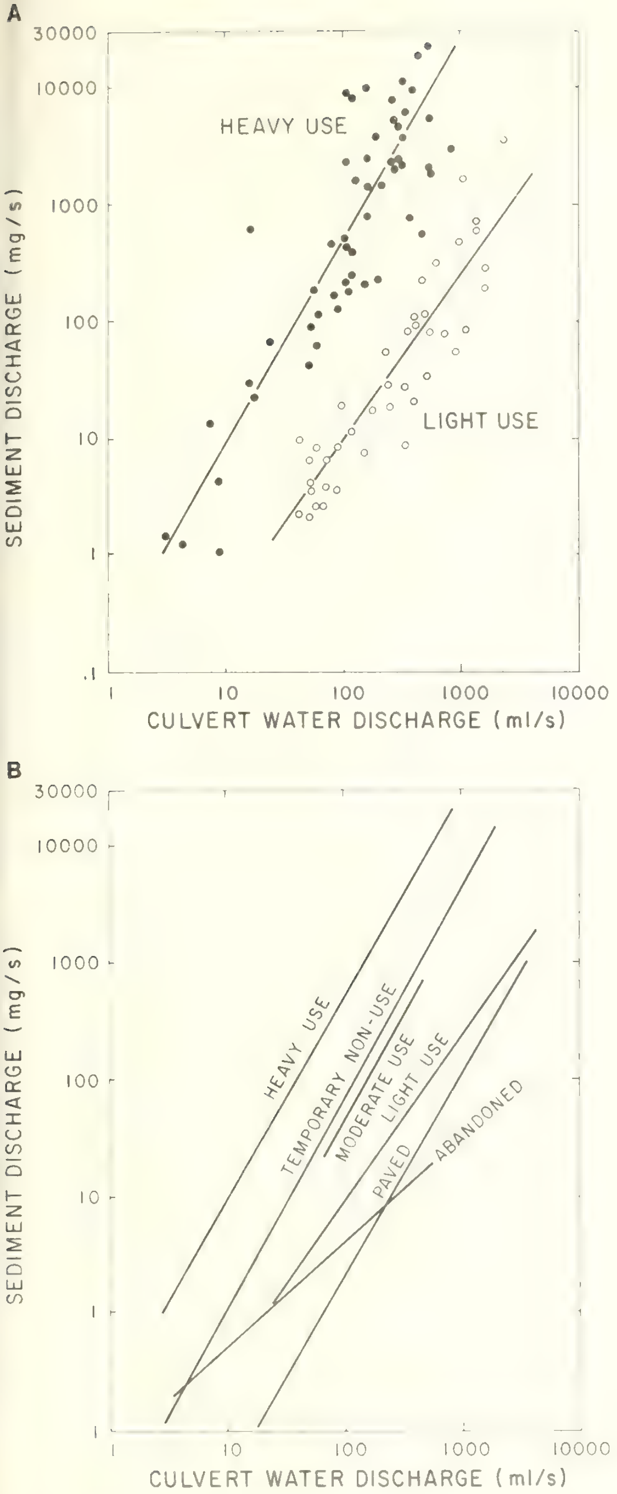


Figure 1.--Effects of road-surface conditions on sediment-discharge rating curves of drainage culverts for gravel-surfaced logging roads in the Clearwater drainage basin of coastal Washington. A. Comparison between "heavy use" (16 to 32 logging trucks/day) and "light use" (no logging trucks in 3 to 60 days). B. Summary diagram comparing different use conditions, including "moderate" (1 to 2 trucks per day) and "temporary nonuse" (logging trucks within past 2 days).

western Washington, Reid (1981) developed a technique for computing sediment influx to streams in a drainage basin that contains a variety of roads experiencing a range of usage. She monitored culvert discharge from 10 road segments of average length and gradient, taking care to avoid segments with significant drainage from a back-cut or hillslope. The roads represented six surface conditions: two segments were paved, two were gravel-surfaced but abandoned, and the remaining six gravel-surfaced segments were used with varying intensity, from heavy (more than eight logging trucks per day) to light (without truck traffic for 3 to 60 days before measurement). Culvert discharge, sediment concentration, and rainfall intensity were measured at each culvert during a series of storms and used to construct unit hydrographs and sediment rating curves for each use-level on each road (fig. 1). The unit hydrographs were then used to generate a continuous record of runoff from a year's continuous rainfall record measured in the basin. Applying the sediment-rating curve to the generated runoff record, Reid computed the annual sediment yield from the road segments under different surface and road-use conditions.

## IDENTIFICATION OF LINKAGES AMONG PROCESSES AND STORAGE ELEMENTS

Linkages among processes and storage elements establish the general form of a sediment budget, which can be expressed in a flow diagram--such as figure 2. Identification of causal linkages in the budget highlights the effects of successive transfers on the characteristics and quantity of sediment moved. For example, in drainage basins free of extensive valley-floor deposits, the particle-size distribution of alluvium is controlled by soil-formation processes and by attrition and sorting during fluvial transport. In low-order channels, stream transport has little opportunity to sort or comminute sediment supplied by slope processes. Residence time of sediment in small, steep tributaries in many areas is probably 100 years or less (Dietrich and Dunne 1978), so chemical weathering probably has little effect on particle hardness. In the long term, the relative proportions of bedload-size and suspended-size particles discharged from these channels must largely reflect the texture of the soil, with the coarsest fraction being transported by debris flows in some regions. Along the floors of higher order valleys, the residence time of sediment in storage is much longer, so that chemical weathering and fluvial transport can lead to dramatic shifts in the particle-size distribution of the load, as coarse particles break into finer sizes. The rate of breakdown is greatly influenced by the degree of weathering of debris in the parent soil. Dietrich and Dunne (1978, p. 200) have summarized field and laboratory evidence for this breakdown, but quantitative applications of laboratory studies to the field setting are still lacking.

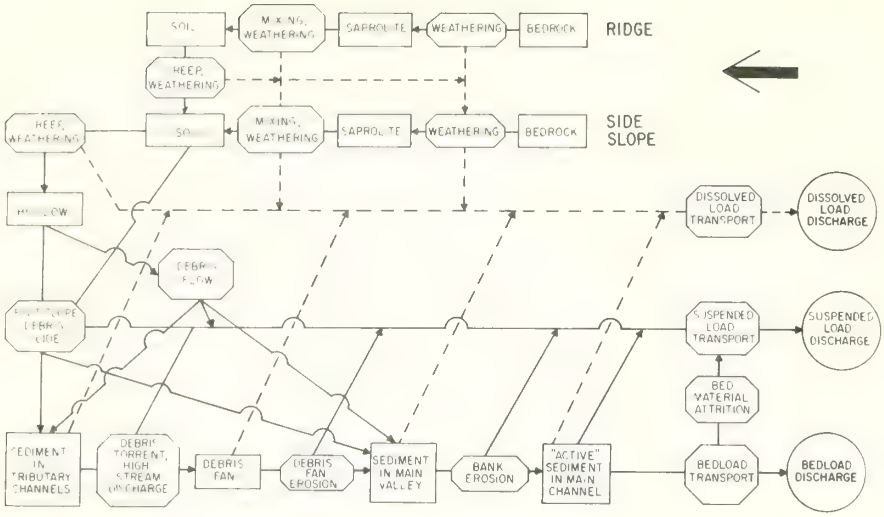


Figure 2.--Sediment-budget model for the Rock Creek basin, central coastal Oregon: rectangles, storage sites; octagonals, transfer processes; circles, outputs; solid lines, transfer of sediment and dotted lines, migration of solutes (from Dietrich and Dunne 1978).

In a previous paper (Dietrich and Dunne 1978), we attempted to show the importance of breakdown of weathered sediment in the 16-km$^2$ Rock Creek basin of Oregon. Sediment with settling velocities less than the shear velocity tends to stay in suspension (e.g., Middleton 1976); and in steep channels in our study area, the settling velocity of 2-mm-diameter sediment (about 21 cm/second) is generally exceeded at high flows by the local shear velocities estimated from the downstream component of the weight of the fluid. About 43 percent of the soil mass discharged into stream channels is less than 2 mm in diameter and would, therefore, travel primarily as suspended load. In gravel-bedded streams of the western United States, measured bedload transport ranges from 4 to 10 percent of the total solid load (Rosgen, D., USDA Forest Service, personal communication, based on many measurements in the Rocky Mountains; Emmett and Seitz 1973, 1974). Higher ratios have been estimated in some small basins (Larson and Sidle 1980). If the ratio of bedload discharge to total solid-load discharge is 10 percent at the mouth of Rock Creek, about 82 percent of the bedload-size material discharged from the soils must break down to suspended load during transport to the basin outlet. This calculation assumes that, over the long time scale, no change occurs in the volume of coarse sediment in storage in the basin. The presence of bedrock at or near the surface throughout most of the Rock Creek drainage network points to the lack of important storage.

The identification of linkages is critically important in distinguishing those erosion processes that are separate additive components of sediment discharge from the processes that are carrying the same material along sequential portions of its path through the basin. In forested mountainous landscapes, a fundamental and yet unresolved problem is the definition of the relation of the ubiquitous--but slow--processes of soil creep and biogenic transport to the rapid transport of sediment by landslides, so that the contribution of each process to the sediment budget can be separated. To investigate this problem for a drainage basin, it is necessary to estimate the relative importance of types of hillslope-transport processes and their distribution within the basin. We have examined this problem in two regions of the low coastal mountains of Oregon and Washington underlain by volcanic and sedimentary rocks.

We first recognized two distinctive soil types. Thin, gravelly soils cover most of the landscape and vary systematically with hillslope angle (fig. 3). Thick, sandy and gravelly soils in U-shaped bedrock depressions, which we have called soil "wedges" (Dietrich and Dunne 1978), show no clear variation with hillslope angle. The wedges (fig. 4), which appear to be filled landslide scars, occur at the headwaters of most first-order tributaries and intersect 10 percent of the perimeter of the first-order channels and up to 50 percent of third- and fourth-order channels. We see no evidence of water erosion in the basins represented in figure 3. In both drainage basins, deep-seated landslides incorporating significant amounts of saprolite or bedrock are rare. Instead, most landslides involve just the soil mantle and commonly emanate from wedges. Because the form of the bedrock depression concentrates subsurface water into wedges, landsliding occurs more frequently there than in surrounding thin soils. The shallow, coarse-textured soils overlie competent weathered bedrock, and we have seen no evidence for active earthflows. In a previous paper (Dietrich and Dunne 1978), we suggested that the creep rate in soil wedges is four times faster than in the surrounding thin soils. This proposal was based on our misinterpretation of field measurements by Swanston and Swanson (1976). Their data pertain only to earthflows associated with large landslides rather than to soil creep. At present, we know of no program of measurements on the discharge from wedges by soil creep.

Soil creep, biogenic transport, and debris sliding are not separate additive components to total discharge of soil into channels. Soil that is finally discharged to the channel by one process may have been carried along most of the slope by other processes. Therefore, the total flux of sediment to channels should not be computed by adding the discharge from debris slides to an

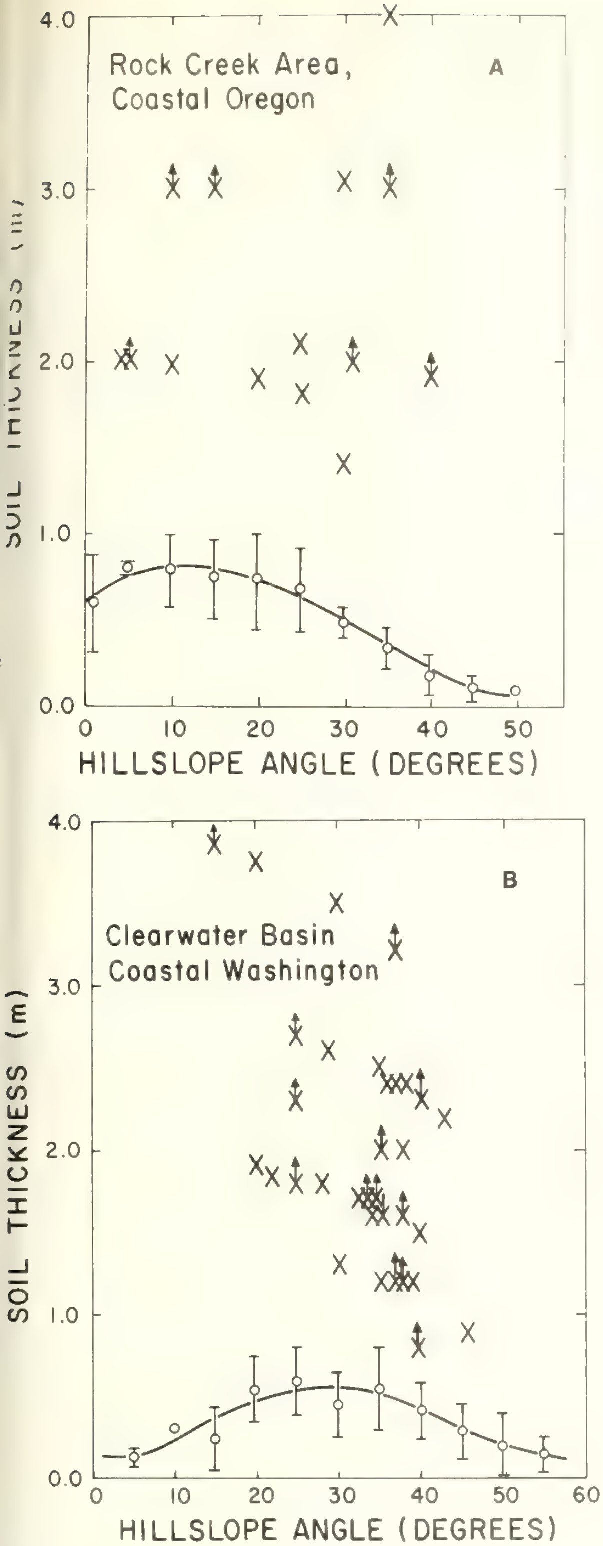


Figure 3.--A. Relationship of hillslope gradient to soil depth for soils in the Rock Creek area of coastal Oregon. B. Clearwater basin of the Olympic Peninsula of Washington. Measurements were made along road cuts. Circles represent the average of depths for 5-degree classes, and the bars are the standard deviations. The crosses represent the depth for wedges and, where the total depth was not exposed, an arrow was attached to the symbol.

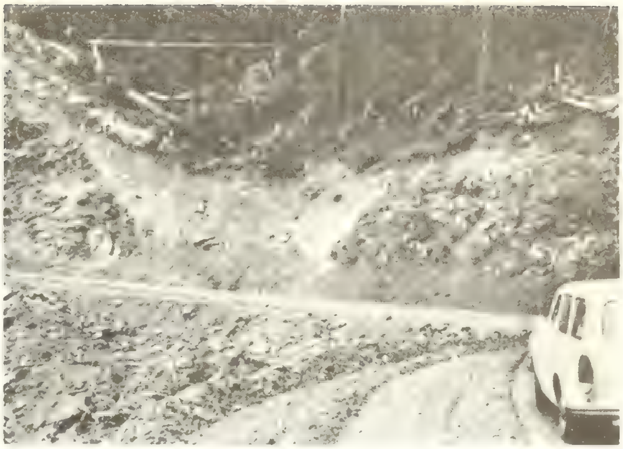


Figure 4.--Soil wedge partially filling depression in sedimentary bedrock, western Olympic Peninsula. Note the characteristic "U"-shaped depression and the great soil depth compared to adjacent areas.

average soil-creep rate. This relationship can be visualized, for example, by examining what happens when a debris slide erupts from a soil wedge.

A debris slide may develop into a debris torrent and scour the channel and footslopes of first- and second-order basins. On the bed and walls of the slide scar, fresh and weathered bedrock are exposed and near-vertical walls are left in the surrounding soils (fig. 5a). After the slide, the bedrock weathers rapidly along fractures and joints; and the vertical soil face degrades through rain splash, raveling, sloughing, and small-scale slumping of soil into the scar. Removal of soil from the face and the steepening and destabilizing of soil upslope also lead to accelerated tree-throw around the margins of the scar and accelerated soil creep. The distance over which accelerated soil movement extends upslope depends on the time and amount of soil required to refill the scar.

Soil initially discharged into the bare scar will be subject to concentrated water flow, and only the coarsest particles will remain in the depression as a gravel layer (fig. 5b). Continued discharge of poorly sorted soil into the scar forms a thickening wedge of partially reworked sediment from which saturation overland flow (Dunne 1978) is generated progressively less frequently. When saturation overland flow can no longer be produced in the wedge, soil discharged into the scar accumulates without reworking by water and thus retains the textural characteristics of the surrounding profile from which it is derived (fig. 5c). Figure 6a illustrates the changes in texture of deposits with time, and figure 6b portrays the rate of filling in hollows as estimated from dendrochronology.

During the early phases of refilling, the scar will be a source of high sediment discharge to the stream. Based on the dendrochronology shown in figure 6b and the corresponding change in sediment texture (fig. 6a), we estimate that this period

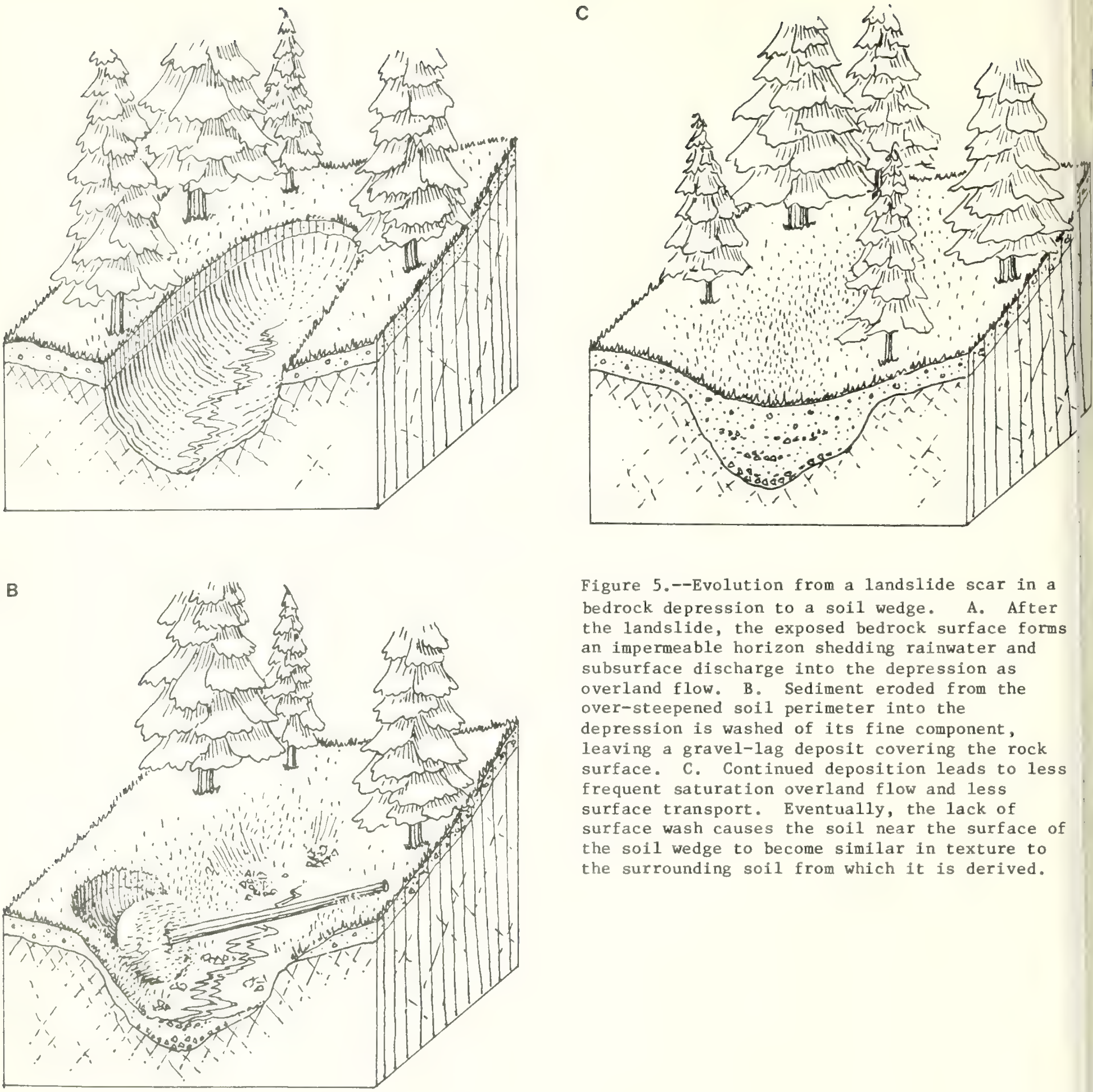


Figure 5.--Evolution from a landslide scar in a bedrock depression to a soil wedge. A. After the landslide, the exposed bedrock surface forms an impermeable horizon shedding rainwater and subsurface discharge into the depression as overland flow. B. Sediment eroded from the over-steepened soil perimeter into the depression is washed of its fine component, leaving a gravel-lag deposit covering the rock surface. C. Continued deposition leads to less frequent saturation overland flow and less surface transport. Eventually, the lack of surface wash causes the soil near the surface of the soil wedge to become similar in texture to the surrounding soil from which it is derived.

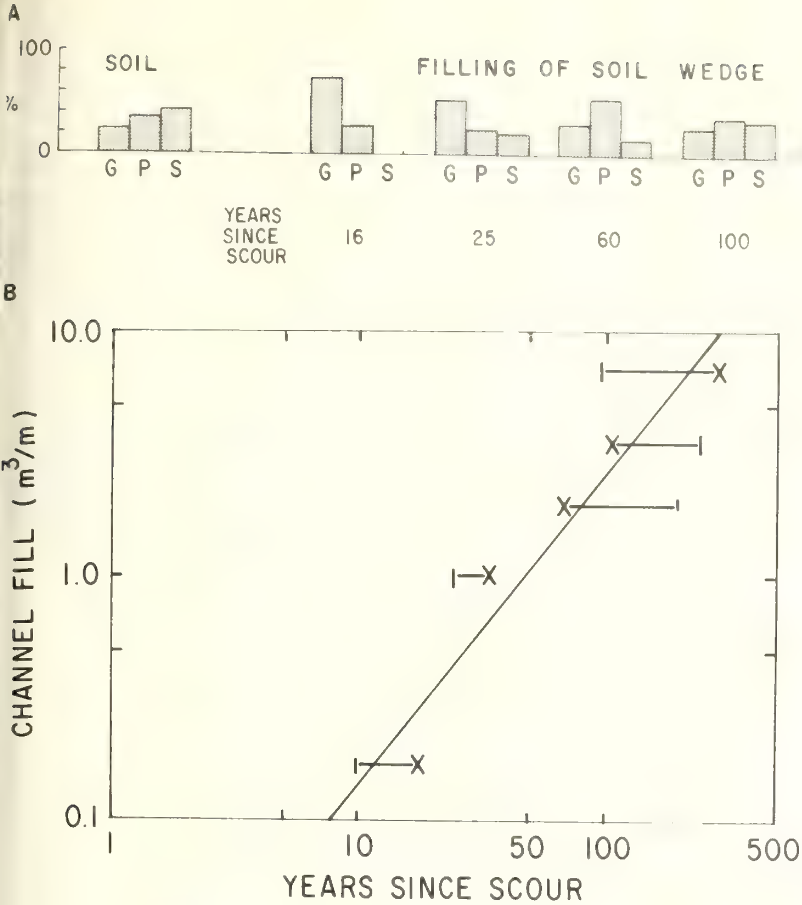


Figure 6.--A. Successive fining of material during filling of hollows. The fraction greater than 22 mm was measured by the pebble-count method of Wolman (1954), and the data were combined with sieve analyses of the finer particles. The letters indicate gravel (g) (greater than 22 mm), pebbles (p) (from 2 to 22 mm), and sand (s) (less than 2 mm). B. Rate of filling of scoured hollows. Time of scour was determined from ages of vegetation on fills. (X) is our best estimate, error bar represents the range of uncertainty in our estimate. Vegetation consisted of salmonberry and alder on more recently scoured hollows, and large alder, hemlock, and Douglas-fir on older, partially filled hollows.

will last about 100 years. By the end of this period, the texture of the upper layer of the wedge is similar to that of the surrounding soil. As the scar fills, sediment discharge from the wedge decreases. The scar may fill completely so that no topographic expression remains, or it may fail during a large storm that occurs as it is filling. During accumulation, sediment discharge from the wedge must be less than prefailure levels. When the filling is complete or when an equilibrium depth is reached that balances the influx and discharge of soil, the latter attains its prefailure rate (fig. 7).

The time required to refill a depression can be estimated by computing a creep discharge rate into the slide scar across its exposed perimeter. For example, a creep rate of 3 mm/year in a 50-cm-thick soil will refill a bedrock depression 5 m wide, 20 m long, and 2 m deep in 3,000 years. This estimate represents a minimum because much of the initial soil discharge into the exposed hollow will be washed out. An increase in the frequency of failure because of a climatic change or management activity would accelerate soil movement towards the scar and thin the surrounding soil over periods of hundreds to thousands of years. Debris-slide scars then probably fill between 1,000 and 10,000 years after initial failure. Although transport into the scar will be accelerated by the sloughing of soil and gullying of exposed soil, the ultimate transport rate into the scar will be limited by the supply of soil and the rate of soil transport toward the location of failure.

On the short time scale for which a quantitative sediment budget might be developed from a monitoring program, debris-slide scars will generally be sources of high sediment discharge. That the period of increased erosion extends for a long time after the slide occurs is well illustrated by Tanaka's (1976) measurements in the Tanzawa Mountains of Japan. His repeated topographic surveys showed rates of sediment discharge from 50-year-old debris scars to be about 100 times greater than the estimated undisturbed rate of sediment discharge from hillslopes. Lundgren (1978) has also reported that in the subhumid mountains of Tanzania, erosion during a 7-year period after formation of landslide scars was as great as the initial loss from the landslides.

If debris slides lead to accelerated weathering of the underlying bedrock during exposure and burial, or if they cause loss of debris from the weathered bedrock in the scar or its surroundings, then a component of their discharge can be defined as a contribution to the sediment budget separate from creep and biogenic transport. Otherwise, debris slides emanating from the soil mantle act more as periodic fluctuations in the rate of discharge of sediment from the hillslope by soil creep and biogenic transport.

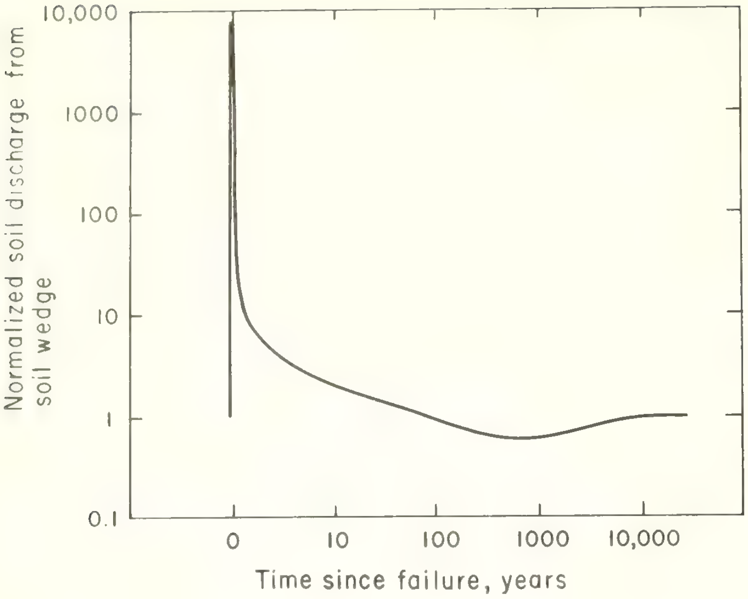


Figure 7.--Chronologic variation of sediment discharge into a stream channel as a result of failure of a soil wedge and eventual refilling of the bedrock depression. The annual sediment discharge for each year was divided by the average annual sediment discharge to normalize the curve.

## DEFINITION OF RECURRENCE INTERVALS

The degree to which one process affects another and the importance of a transport process to the sediment budget are both dependent on the magnitude and frequency of recurrence of the process at a place. Definition of the probability distribution for some transport processes (e.g., sheetwash from roads) is relatively easy. Definition of a recurrence interval of landslides is a difficult problem in steep, forested drainage basins, however. Frequency of landsliding depends on the stochastic properties of external controls--such as storm intensity, antecedent weather, and earthquakes. The importance of these controls at a site will depend on specific site conditions such as soil permeability, vegetation cover, groundwater flow path, and soil strength. The frequency of landsliding, then, needs to be specified at a site. In the Coast Ranges of Oregon and Washington, landsliding occurs with varying frequency from topographic hollows, filled bedrock hollows, and planar slopes. A regional landslide frequency cannot be applied to a specific site, unless all the failures used to define the regional frequency originate from the same type of site (e.g., filled bedrock depressions at the heads of valleys). Then space can be substituted for time in the calculation of recurrence interval.

Estimates of regional rates of landsliding can be obtained from sequential aerial photographs and from dendrochronology, but the occurrence of major storms confounds a simple computation of long-term frequency of these events. No simple correlation can be made between recurrence interval of the hydrologic event and the recurrence of landsliding because of site-specific controls on the hydrologic events and because of lag effects resulting from long recovery times from previous landsliding. Similarly, landsliding caused by earthquakes cannot be simply related to the frequency of occurrence of the earthquakes, as done by Garwood et al. (1979). Long periods of record and large samples will eventually allow the definition of useful mean recurrence intervals from each type of site, but--at present--the aerial photographic record is too short for accurate determination of recurrence intervals.

Definition of recurrence interval becomes particularly difficult when the landslide is not an instantaneous discharge of soil into a channel but is a deep-seated failure that moves episodically. Not only is relating the movement to the probability of occurrence of the specific site conditions and hydrologic events difficult, but to generalize the probability of failure to similar sites is extremely difficult. This problem is further complicated by the tendency for slumping to generate debris avalanches at the channel perimeter (Swanson and Swanston 1977), creating an interdependency of frequency and magnitude between different processes.

Landslide frequency is traditionally defined for a large area from sequential aerial photographs without specification of landslide site conditions. This frequency is assumed to apply to basins of any size in the area. Not only does this approach neglect effects of major storms, but it also ignores the effect of basin size, which clearly influences the range and frequency of site conditions. The effect of basin scale is an important one and has been discussed by Wolman and Gerson (1978) as it applies to stream morphology.

Quantitative definition of the role of landsliding in a sediment budget can be approached in several ways. For the simplest case in which landsliding involves just the soil mantle and essentially represents the last step in the transport of soil to the stream channel, the problem of recurrence interval can be ignored as long as some estimate can be made of the rates of hillslope transport by other processes. This is only appropriate, however, in a sediment budget for a long period during which it can be assumed that the transport processes are in equilibrium and major landforms are not changing substantially.

Another approach would be to construct a sediment budget for a specific interval only and not to develop a predictive model of the transport processes. Only landslides generated within the study basin would be considered. Similarly, only measurements of other processes within the basin would be used. The value of this procedure depends greatly on the length of time over which measurements can be taken. This method, however, allows semiquantitative examination of the effects on landsliding of major differences in basic controls such as geology, climate, or land use.

We have suggested above that a regional landslide frequency analysis could be made for specific sites, particularly if the time base can be expanded using dendrochronologic or other dating techniques. The frequency of site types within a basin would then be used to construct a sediment budget. This problem is also discussed by Kelsey in his Discussion Group Summary for this workshop. Although confusing effects of unequally distributed meteorologic events and stand history would degrade the quantitative results, this procedure would yield a meaningful, predictive sediment budget.

The most general approach in the long term would be to develop models for hillslope instability. In the simple case in which debris slides are caused primarily by adverse combinations of soil strength and high pore-water pressure, recurrence interval of landsliding at a site may eventually be defined through a combination of a deterministic model of hillslope stability, a deterministic model of pore-water pressure generated by precipitation, and a stochastic expression for precipitation occurrence. Included in this model would be the change of soil depth with time as the site refilled from the previous landslide. Regrettably, definition of recurrence of landsliding is not an easy problem.

## QUANTIFICATION OF STORAGE ELEMENTS

Sediment storage elements in the landscape are the medium through which transport processes act, and therefore their quantification is of great importance in the construction of a sediment budget. To discuss the characteristics of different types of storage elements (or sediment reservoirs) in a drainage basin and to examine their interaction, we briefly define a few essential terms used in reservoir theory as presented most simply in Eriksson (1971) and Bolin and Rodhe (1973). A variety of sediment reservoirs exist in a drainage basin, ranging from vast quantities of debris stored in the soil mantle on a hillslope to small accumulations in gravel bars. Each accumulation can be characterized by the age distribution of sediment in the reservoir and the age distribution of sediment leaving the reservoir. Age is used here to mean the time ($\tau$) since the sediment entered the reservoir. The first distribution could be defined in the field by dating the deposits in a reservoir and by developing the cumulative curve of mass $M(\tau)$ in the reservoir, less than or equal to a certain age ($\tau$) such that

$$\lim_{\tau \to \infty} M(\tau) = M_0 \qquad (1)$$

where $M_0$ is the total mass of the reservoir. Everitt (1968), for example, aged flood-plain deposits on the Little Missouri River using dendrochronology. Taking the derivative of this cumulative curve, with respect to the age of sediment, creates an age-distribution function $\psi(\tau)$, where

$$\psi(\tau) = \frac{1}{M_0} \frac{dM(\tau)}{d\tau} \quad . \qquad (2)$$

The average age of sediment in a reservoir, $T_a$, can be computed by integrating the cumulative curve with respect to mass and dividing by the total mass, which is equivalent to computing a weighted mean age (Eriksson 1971):

$$T_a = \frac{1}{M_0} \int_0^{\infty} \tau dM(\tau) \qquad (3)$$

$$= \int_0^{\infty} \tau \Psi(\tau) d\tau \quad . \qquad (4)$$

For many sediment reservoirs, the age-distribution function will be impossible to define unless the reservoir contains natural tracers, such as vegetation and tephra, or artificial tracers, such as isotopic lead (Barnes et al. 1979), radioactive fallout (Ritchie et al. 1975), painted rocks (e.g., Laronne and Carson 1976), and anthropogenic debris (Costa 1975). These tracers need to be distributed in time for periods of centuries and in space for sites representing the range in age in a reservoir to yield meaningful results about most sediment reservoirs. If sediments of different ages become well mixed, however, quantitative evaluation of the age-distribution function will be difficult.

Reservoirs can also be characterized by the age distribution of sediment leaving the reservoir. If it were possible to evaluate the time spent in storage for each particle that leaves the reservoir, then for a particular time increment, a cumulative curve of discharged mass of sediment leaving the reservoir less than or equal to a certain age, $F(\tau)$, could be constructed. This curve is called a "transit time" function because it gives the distribution of transit times through the reservoir for the discharged sediment. As $\tau$ becomes very large, $F(\tau)$ approaches the total flux per unit time out of the reservoir:

$$\lim_{\tau \to \infty} F(\tau) = F_0 \quad . \qquad (5)$$

As in equation 2, the derivative of the cumulative curve with respect to age yields the distribution function of transit time:

$$\Phi(\tau) = \frac{1}{F_0} \frac{dF(\tau)}{d\tau} \quad . \qquad (6)$$

The average transit time of sediment discharged from the reservoir, which is defined to be the residence time of the sediment in the reservoir (Bolin and Rodhe 1973), is the integral of the cumulative curve of transit times divided by the total flux per unit time:

$$T_t = \frac{1}{F_o} \int_o^{\infty} \tau \, dF(\tau) \qquad (7a)$$

$$= \int_o^{\infty} \tau \Phi(\tau) d\tau \quad . \qquad (7b)$$

Characterization of transit times from field measurements of sediment discharged from a reservoir is extremely difficult. Most studies that attempted to define transit times have been for fluvial transport processes and used painted rocks. These studies have failed to recognize three important aspects of sediment reservoirs, however, and as a result they have not yielded useful information.

First, it is necessary to recognize that measurements of the movement of marked particles is a transit-time study of a particular reservoir or set of interacting reservoirs, and, therefore, defining the various types of reservoirs in an area and their boundaries is also necessary. In fluvial studies, at least two types of reservoirs may be recognized: flood plains, bars, and active streambed. The computed residence time of particles in these reservoirs will depend partly on the exchange rate between reservoirs and on the definition of reservoir boundaries. Second, transit time of sediment depends on where in a reservoir the marked particles are placed. In stream channels, the particle-size distribution of the bed material across the channel is a function of the boundary shear-stress distribution. If the goal is to typify the transit-time characteristics of the reservoir, introduced marked particles must duplicate the particle-size distribution across the channel. Further, the particles must be placed throughout the active depth of the channel sediment, not just at the surface as is normally done. This consideration may make a difference of greater than 20 times in the measured transit times of particles (based on computations by Dietrich and Dunne 1978). Third, to compute transit times, all particles must be recovered. Unfortunately, recovery rate of marked particles is generally very low; following all particles without seriously disturbing the reservoir would be nearly impossible. Regrettably, this last problem is a major constraint. We will address the problem again later. Further discussion of the theory of tracers can be found in Eriksson (1971) and Nir and Lewis (1975).

Definition of the residence time of sediment in a reservoir from measurement of transit times is difficult. As an alternative, residence time can sometimes be computed from the age distribution o estimated average age of sediment in the reservoi. Eriksson (1971) has shown that under steady-state conditions, as sediment of a particular age leave the reservoir, a corresponding aging of sediment remaining in the reservoir must occur, such that

$$F_o - F(\tau) = \frac{dM(\tau)}{d\tau} \quad . \qquad (8a)$$

The left side of equation 8a gives the amount of sediment greater than age $\tau$ that leaves the reservoir per unit time. To maintain a steady-state age distribution, the amount of sediment with an age greater than $\tau$ that remains in the reservoir must increase at a rate equal to this rate of efflux, as given by the right side of the equation. The derivative with respect to $\tau$ of each side of the equation yields the transit-time density function,

$$\frac{dF(\tau)}{d\tau} = - \frac{d^2M(\tau)}{(d\tau)^2} \quad . \qquad (8b)$$

Although the transit-time function can be compute from the age distribution of sediment in the reservoir from equation 8b, the function is very sensitive to small errors in definition of the ag distribution and can only be done practically for poorly mixed or unmixed reservoirs. Such a reservoir might be a flood plain constructed predominantly by lateral accretion of bedload on point bars. A simple example, however, illustrat that even in a poorly mixed reservoir such as a flood plain, the age distribution may be time- an space-dependent.

Consider the simple case, illustrated in figure 8 of a stream channel migrating uniformly across it flood plain at the rate of one channel width per year. If the deposits were sampled when the channel was in the three positions in figure 8a, b, and c, the average age according to equation 3 would be 5.5, 8.0, and 6.4 years, respectively. This time dependency may be overcome in the field by expanding the upstream and downstream boundaries of the reservoir so that the channel position ranges back and forth across the valley floo at any time.

To examine the relation between residence time and average age, consider two steady-state models of a gravel bar illustrated in figures 9a and b. This first is a piston model in which gravel enters at one end of the reservoir and leaves exactly 10 years later. Clearly, the residence time of the gravel in the bar would be 10 years, and the average age of the sediment would be 5 years. By contrast, in the second model, although the annual discharge rate is the same, 60 percent of the gravel in any year enters and leaves the reservoir while the other 40 percent becomes deeply incorporated in the bar and takes 25 years to leave the reservoir. The average transit time of sediment leaving the bar is (0 x .6) + (25 x .4) = 10 years the same as in the first model. But the average age of sediment in the reservoir will be 13 years.

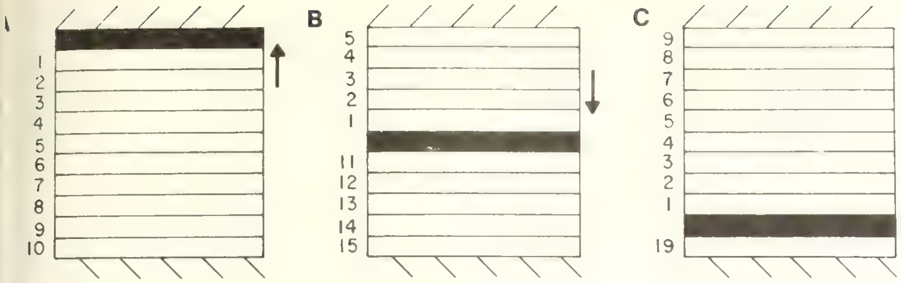


Figure 8.--A-C. Change in age distribution of flood-plain sediment reservoir resulting from uniform lateral migration of the active channel (darkened area) at one channel-width per year. Numbers in columns give age in years for each increment of flood-plain deposit.

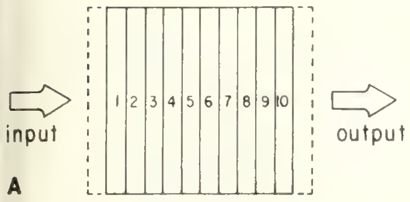
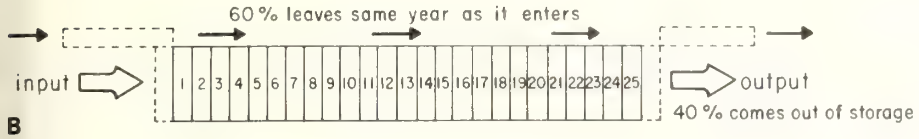


Figure 9.--A-B. Two models of transfer of sediment through a gravel bar. Numbers are the age of the sediment in particular parts of each reservoir. Total sediment flux rate is the same for both models but, in the second, 60 percent sediment entering the reservoir leaves immediately, and the remaining 40 percent travels slowly through the entire reservoir.



Bolin and Rodhe (1973) have demonstrated that even in steady-state reservoirs, average age of sediment may be less than, equal to, or greater than the residence time. They also showed mathematically that the turnover time of a reservoir defined as the total mass in the reservoir ($M_o$) divided by the total flux rate ($F_o$) equals the residence time of sediment in a reservoir in the steady-state condition:

$$T_r = \frac{M_o}{F_o} \quad . \qquad (9)$$

Where the reservoir can be treated as if in steady state, the estimated residence time becomes a much more tractable problem. In the short period of a few years, most storage elements in a landscape are probably very poorly represented by the steady-state assumption. Over the long period, however, the average quantity of sediment in storage in some reservoirs may be considered relatively constant. For example, in small alluvial valleys with steep hillslope boundaries in which the channel is close to bedrock, the assumption of steady-state storage of sediment in the flood plain is probably reasonable over a period of a few decades, particularly if the sediment flux into and out of the foodplain occurs primarily by bank erosion and channel migration rather than by episodic deposition or scour by debris torrents.

A river-valley segment of the Little Missouri River of western North Dakota which approximately meets these requirements was intensively surveyed by Everitt (1968). He mapped the age distribution of cottonwood trees on a 34 000-m-long length of flood plain formed by a freely meandering, 91-m-wide, sand-bedded river in a 900-m-wide valley. At the time of the study, the channel had recently cut off two large bends and was subject to ice jams that caused it to shift rapidly across its flood plain. As a result, the density function of flood-plain area occupied by sequential 25-year age classes of sediment was negatively exponential. From Everitt's data on the area and elevation of sediment above low water in various age classes, we have computed an approximate age-distribution function, $M(\tau)$, for the volume of sediment in the flood plain. The derivative of this function is the right side of equation 8a; if one can assume that no flood-plain sediment enters and leaves the reach in the same year (i.e., $F(\tau) = 0$ when $\tau = 0$), equation 8a can be used to obtain $F_o$, the flux rate of sediment through the reservoir. Everitt fitted a power function to the height above low water of flood-plain sediment of various ages and obtained results similar to the following by a different technique. We used the power function of height and the exponential function of area to compute the age-distribution function, $M(\tau)$, which was integrated to obtain a total volume of sediment, $M_o$, of $1.08 \times 10^7$ m$^3$. Differentiating $M(\tau)$ with respect to $\tau$ yields the right side of equation 8a and, therefore, at $\tau = 0$, a flux rate, $F_o$, of $1.08 \times 10^5$ m$^3$/year. Substituting this value and $M_o$ into equation 9 leads to a residence time of 100 years.

The transit-time function for Everitt's data (obtained by twice differentiating M(τ), substituting into equation 8b, and integrating the left side) suggests that most of the sediment spends less than 1 year in the flood plain. This counterintuitive result may be an artifact of using a power function to express the height of the flood plain above low water for a given age because this combines with the exponential curve for the area-distribution function to place the bulk of the flood-plain sediment in a very young age-class.

Another reservoir that might be treated as having a constant volume in storage over long periods is the debris fan. The volume of a fan has generally been found to be a power function of the drainage area of the basin contributing to it (Bull 1964). We have also found this relationship for a small drainage basin in coastal Oregon (fig. 10a). If the long-term average annual discharge into or out of the fan can be estimated from short-term measurements, then the average residence time in a debris fan can be computed approximately from equation 9.

A third reservoir that might more commonly be in steady state is the "active" channel sediment that comprises all of the sediment in the channel bed, including gravel bars, down to a rarely attained maximum scour depth and across to channel boundaries marked either by a distinct bank or by vegetation changes. "Active" sediment is not a meaningful term in some low-order tributaries where sediment is moved primarily by episodic debris torrents. Unless channel storage is changing dramatically from modifications in channel geometry in response to a significant change in sediment load or flow characteristics, the "active" stored sediment in, say, a length of channel of about 10 channel widths is roughly constant, even in aggrading and degrading streams. If the flux rate along the channel and into or out of the flood plain can be estimated, then residence time can be computed.

The time scale that defines the period over which steady state is to be assumed is proportional to the residence time of sediment in the reservoir. If disturbances in flux rate occur over the same time scale, then steady state is a poor approximation. Also, many disturbances from forest management occur on a time scale shorter than the period over which steady state might be assumed. Nonsteady state implies the sediment reservoir is not only characterized by age distributions but also by absolute time. We know of no simple general theory for dealing with the nonsteady state although work has been done toward that end (Nir and Lewis 1975, Lewis and Nir 1978).

In both the steady- and nonsteady-state cases, another approach to computing residence time and developing a sediment budget is to construct a transition probability matrix to define the flux into and out of one reservoir and into another. For example, consider the transport of sediment along an alluvial valley floor. Two general sediment-storage elements, the active channel (defined above) and all the other flood-plain deposits, can be quantified by surveying; the

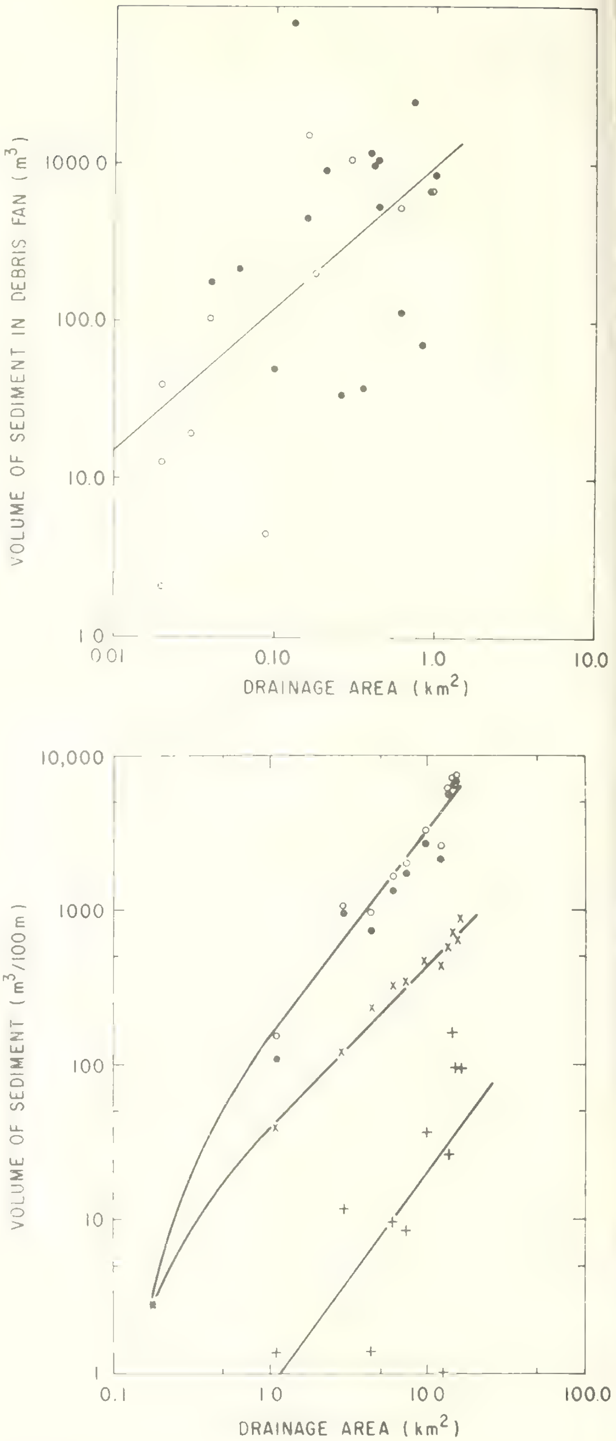


Figure 10.--A. Volume of debris fans as a function of tributary drainage area along the main channel of the 16.2-$km^2$ Rock Creek drainage basin, Oregon. Open circles are debris fans covered by salmonberry and young alder trees. Dots are fans covered by more mature trees. B. Volume of sediment in gravel bars (pluses), "active" channel (crosses), flood plain (dots), and total valley sediment (open circles) along the main channel of Rock Creek. Equations for least squares fit to the data in 10A and B are given by Dietrich and Dunne (1978).

amount of sediment in storage can be related to distance along the channel from headwaters (fig. 10b). The sediment in storage per unit length of channel can be depicted by the column matrix

$$V = \begin{vmatrix} x \\ y \end{vmatrix}$$

where x and y are the volume of sediment in storage per unit length of valley in the active channel and the flood-plain deposits, respectively.

The exchange between the two reservoirs caused by such channel changes as migration, widening or narrowing, or downcutting can be represented by the transition probability matrix

$$S = \begin{vmatrix} a & b \\ c & d \end{vmatrix}$$

where the first row represents the proportion per unit time of the total sediment in the active channel that either remains in the active channel (a) or is transferred to the flood plain (b). Similarly, (c) is the proportion of flood-plain sediment eroded into the active channel, and (d) is the proportion that remains. If the transpose of S is taken and this new matrix $S^T$ is multiplied times V, a column matrix is formed by the product expressing the amount of sediment in the two reservoirs as a result of the exchanges specified by S.

The input and output of sediment can be represented by column matrices $Q_i$ and $Q_o$, respectively,

$$Q_i = \begin{vmatrix} i \\ j \end{vmatrix} \quad \text{and} \quad Q_o = \begin{vmatrix} k \\ m \end{vmatrix}$$

where i and j are the volumes per unit time added to the active channel and flood plain; k and m are the volumes discharged from each, per unit time. Values other than zero for j and m occur as a result of overbank flow. The net increase or decrease of sediment stored in each reservoir after a unit time is given by the column matrix

$$\Delta V = \begin{vmatrix} r \\ s \end{vmatrix} \quad .$$

The continuity of mass per unit length of channel can now be written as

$$V - S^T V + Q_i = Q_o + \Delta V \quad . \tag{10}$$

This is a general equation for any system of reservoirs in steady or nonsteady state. In many sediment routing problems, each term can be quantified approximately from fairly simple field measurements. A valuable way to use equation 10 would be to establish a series of surveyed cross sections across the valley floor. Repeated survey at these sections, recording of channel scour depths with scour chains, and measuring of sediment transport both in the channel and on the flood plain at the upstream and downstream end of the channel length should allow computation of a sediment budget using equation 10. In this form, equation 10 has very little predictive value. In the nonsteady-state problem particularly, it is best thought of as the basic mass balance into which field measurements are placed to define the routing of sediment.

At steady state, however, no change takes place in storage ($\Delta V = 0$); although $(i + j)$ must equal $(k + m)$, $Q_o$ need not equal $Q_i$. This inequality could occur by the deposition of flood-plain sediment during overbank flow being compensated for by bank erosion of flood-plain sediment into the active channel. In other cases, equation 10 can be greatly simplified if a steady state exists and $Q_o = Q_i$, such that

$$V - S^T V = 0 \quad . \tag{11}$$

Given that V is known, an infinite number of $S^T$ matrices can solve equation 11, but the actual values of a, b, c, and d are related by the simplification of the two linear equations represented by the equation

$$xb = yc \quad . \tag{12}$$

This simply states that volumes exchanged between the flood plain and the active channel must be equal. Thus, in the steady state described above, if the volume of sediment stored in each reservoir is known and if a single term can be defined in S, such as the annual rate of bank erosion, then the other three terms can be computed. In the steady-state case, the sediment budget can be defined from simple field measurements and, according to equation 9, the residence time for sediment in the active channel ($T_{ra}$) and in the flood plain ($T_{rf}$) is

$$T_{ra} = \frac{x}{xb + i} \tag{13a}$$

$$T_{rf} = \frac{y}{yc + j} \quad . \tag{13b}$$

These residence times are the average time a particle spends in the reservoirs. If the question is how long on the average sediment will take to move some distance along the valley, however, flux rate must be defined in terms of transport across the upstream and downstream ends of the reach, including transport along the flood plain. Exchange between the flood plain and the active channel has no effect on the residence time in the valley floor. Channel migration influences residence time of sediment in the separate reservoirs, but it does not affect the downstream transit time unless downstream flux rates are dependent on rates of bank erosion.

Consider three possible transport relationships for the two major reservoirs defined above. In the first case, no exchange occurs between reservoirs. $S^T$ becomes the identity matrix, and the residence time, which is equal to the average travel time per unit length of the valley, is x/i and y/j for the transport through the active channel and the flood plain, respectively. In a more realistic case, some exchange rate occurs between the two reservoirs, typically by channel migration, but the transport of sediment along the flood plain occurs at an insignificant rate. Thus the residence time of sediment in the valley floor ($T_{rv}$) is

$$T_{rv} = \frac{x + y}{i} \tag{14}$$

because $j \cong 0$. The residence time for sediment in the flood plain alone is given by equation 13b which simplifies to 1/c, the inverse of the probability of transition from flood plain to channel in S. The residence time of a particle in the active channel alone is given by equation 13a.

Thus, the residence time in the active channel is always much less than the residence time of sediment in the valley floor. The residence time for sediment in the flood plain can be greater than or less than residence time for the valley floor because, in the present analysis, residence time in the flood plain refers to the time since the previous transfer of a particle into the flood plain, either from the channel or from upstream. In many rivers, flood-plain sediment transport and reservoir exchange are common. In this case, the average transit time becomes

$$T_{rv} = \frac{x + y}{i + j} \tag{15}$$

and the residence time in the flood plain decreases to that given by equation 13b.

Sediment storage and sediment transport rate are functions of distance downstream (fig. 10), and equation 14 can be integrated to compute the average travel time between two positions along a channel. The integrated equation is given in Dietrich and Dunne (1978). Integration of equation 15 will yield a slightly more complicated form of equation 2 in Dietrich and Dunne (1978).

These results also suggest a way of overcoming some of the problems associated with marked-particle studies in stream channels. If transit time between two positions along the channel is computed for several years for a group of marked particles, part of the transit-time function can be defined. Using calculated average transit time from the integral forms of equations 14 and 15, a function might be fitted to the data to extend it to the longer period needed for complete determination. The transit-time function given by equation 6 probably has an exponential form for most rivers and, therefore,

$$\Phi(\tau) = \frac{dF(\tau)}{F_o d\tau} = me^{-n\tau} \tag{16}$$

where m and n are constants that can be determin experimentally from successive years of measurement of the proportion of total marked particles passing the downstream position. Substitution into equation 7b and integration yields:

$$T_r = \frac{m}{n^2} . \tag{17}$$

Equation 17 can then be used to improve estimate made from short-term, marked-particle studies.

The transit time between two positions along a small channel in a narrow valley can be defined using marked particles in the following manner. At two or more sections along the channel, obliqu troughs across the bed of the stream could be installed that trap all bedload and generate a vortex current that transports the sediment acros the channel to a pit (vortex bed sampler, Milhous 1973). All particles in the upstream pit would b painted, or otherwise marked, and replaced in the channel downstream. A new color code could be used for each flood or season. Sediment returned to the channel would subsequently be captured in the next downstream vortex sampler, yielding the transit time between sections. All marked particles need not be followed because only the marked particles that pass into the lower trough must be counted. The form of the transit-time function would depend on distance between samplin troughs, and establishing more than two sections would permit examination of this dependency. Although such a monitoring scheme would probably only work on small streams, the general form of the transit-time function might be generalized to larger streams.

Because transit-time functions for sediment transport in river valleys are probably not normally distributed, the average transit time (residence time) may be a very poor indication of time spent in a reservoir for the bulk of sediment that moves through a reservoir. For example, sediment passing downstream along a valley floor may have a long residence time because of a small exchange rate with a large flood plain deposit, although most of the sediment leaving the valley-floor section may have traveled quickly through the reservoir along the surface of the channel bed. To quantify the lag times between input of sediment and discharge from a reservoir, and to examine such problems as quantifying the period over which sediment experiences different chemical weathering environments, one must attempt to define the transit-time distribution.

## CONCLUSION

A sediment budget for a drainage basin provides a quantitative accounting of the rates of production, transport, storage, and discharge of detritus. Its construction requires: recognition and quantification of transport processes, recognition and quantification of storage elements, and identification of linkages among transport processes and storage sites. To accomplish this task, it is necessary to know the detailed dynamics of transport processes and storage sites, including such problems as defining the recurrence interval of each transport process at a place.

Qualitative and semiquantitative fulfillment of these requirements help in designing preliminary field studies and determining the general form of a sediment budget for a particular basin. This approximate budget can then be used to design long-term studies. Much progress is still needed in making useful field measurements and developing physically based models before complete, quantitative sediment budgets can be constructed.

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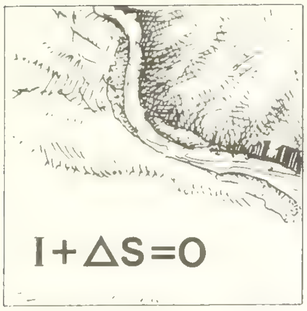

# Modeling of Water and Sediment Yields From Forested Drainage Basins

Daryl B. Simons, Ruh-Ming Li, Timothy J. Ward, and
Larry Y. Shiao

ABSTRACT

Wise management of land and water resources in forested drainage basins requires knowledge of the interrelations within the forest environment and the numerous controlling physical processes. One aspect of drainage-basin response to management activities is changes in water and sediment yields. An important approach for predetermining these yields is through use of water and sediment routing and yield models. Models based on the physical processes controlling erosion provide a realistic simulation of natural and management influences on drainage-basin response. We discuss general concepts of mathematical modeling with particular emphasis (including examples from forested drainage basins) on surface erosion physical-process simulation models developed at Colorado State University.

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Daryl B. Simons, Associate Dean of Engineering and Professor of Civil Engineering, Colorado State University, Fort Collins, Colorado 80521; Ruh-Ming Li, Associate Professor, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado 80521; Timothy J. Ward, Associate Professor, Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico 88001, formerly Assistant Professor, Colorado State University; Larry Y. Shiao, Western Area Power Administration, Department of Energy, Golden, Colorado 80401.

## INTRODUCTION

### Need for Modeling

Increases in development of land and water resources have promoted beneficial and adverse activities in forest drainage basins. One aspect of drainage-basin response is changes in water and sediment yields brought about by different management activities. Drainage-basin sediment yield reflects the change in land-surface erosion, which contributes much of the fine sediments carried in larger rivers. Recent studies have shown that, in addition to other impacts, fine sediment is extremely important for transporting adsorbed substances such as pesticides and other organic compounds.

Accurate methods for estimating changes in water and sediment yields from forested lands are needed to help evaluate related adverse impacts on aquatic and terrestrial ecosystems. One approach is through use of mathematical models that simulate the movement of water and sediment from forested drainage basins. With such models, a forest planner can estimate changes in water and sediment yields brought about by different management activities. Insights gained from model simulations can help the forest planner in formulating development strategies that meet short- and long-term goals.

Mathematical models also aid the conceptualization and organization of drainage-basin system processes. Developing a model emphasizes the strong and weak links in our knowledge of forested drainage basins. Recognition of the weak links, such as subsurface flow, helps direct future research.

Although many computer models are available for predicting water yield, few models have been developed for sediment routing and yield. Water routing is essential for determining sediment movement and resultant aggradation, degradation, and water quality; therefore, water routing and yield are necessary for determining sediment routing and yield.

### Scope of Paper

This paper pesents general concepts of mathematical modeling of water and sediment yields from drainage basins with emphasis on sediment yield from surface erosion of the sheet-rill type. The three other major types, however--landslide, gully, and channel erosion--are discussed in their context with the overall sediment yield of drainage basins. Physical-process models have been singled out and developed in preference to other modeling approaches because they are more representative of the system being simulated, they require fewer sets of data to develop, they are not specific to a particular site or period, and they more readily reflect land-use changes or other activities in the drainage basin. Selected physical-process models are presented with applications to forested drainage basins.

## CONCEPTS OF MATHEMATICAL MODELS

### Model Types

Several types of mathematical models may be used by forest hydrologists. These include "black box" or lumped parameter, regression, stochastic, and physical-process types. A physical-process approach is developed in this paper; however, certain criteria are required for all types of mathematical models.

### Criteria of Useful Mathematical Models

Mathematical models useful for predicting response of drainage basins to natural or management changes should meet the following criteria: (1) The temporal (time) resolution should be adjustable to both short- and long-term response of the drainage basin; (2) the spatial (space) resolution should be flexible from small to large drainage basins; (3) the modeling approach should be transferrable between drainage basins; (4) the model should correctly represent the effects of management activities with selected input variables; (5) uncertainties caused by variability of climate and space should be considered in the model; (6) the model should be usable within the constraints of reasonably available data; (7) the model should be usable by management personnel and scientists; (8) the model should accommodate different levels of accuracy and resolution in the simulations, based on the accuracy and resolution of the input variables; (9) model development should adopt a modular approach that builds a coordinated nucleus of standardized system components for use in a wide spectrum of drainage-basin and river systems; and (10) the model should be well documented so that it can be easily understood and correctly applied. In addition to these attributes, model complexity and resultant data needs should be considered.

### Model Complexity and Data Needs

Potential users of a model are concerned that it may be too complex to use, may not correctly reflect the controlling processes in a drainage basin, or may require data that are extremely difficult to obtain. The flexibility of physical-process models provides a means for resolving these common problems.

To gain precision, a model must simulate the physical processes in the finest possible scale. This often leads to a complex division of the drainage basin and rigorous mathematical treatment of the physical processes. Complex mathematical treatments are not easily understood by many users, who may reject it for a more comfortable but less sophisticated approach. This need not happen if the model is clearly stated and formulated so that the user can examine each physical process. In many applications, a complex and extremely detailed model is not necessary and simpler versions can be used. Model simplification, if the basic physical processes are left intact, need not reduce the applicability of the model.

If a model is organized as a group of modules or subroutines, it can easily be modified to account for variations in the controlling physical processes in a study area. For example, in the Beaver Creek Watershed near Flagstaff, Arizona, runoff processes are dominated by overland flow, and subsurface flow is negligible. Thus, only overland flow and channel flow modules are necessary for adequate modeling of runoff. In contrast, runoff from the H. J. Andrews Experimental Watershed is almost entirely a result of subsurface flow. Surface runoff modules are minor and may be removed, with subsurface-flow routines being substituted. An alternative to a modular-type approach would be an all-purpose, generalized model, but this type of model often requires inputs for routines that do not reflect the controlling processes. Such "overkill" in modeling can lead to user dissatisfaction, increased data preparation costs, and erroneous results. The modular approach also lends itself to efficient updating of a program. As applied research in drainage-basin hydrology and hydraulics advances, new or improved mathematical descriptions of the controlling processes appear. If, for example, a better subsurface flow routine is developed, then it can be substituted as needed into the appropriate models. A modular-type model allows the user to select the physical-process components that best describe the controlling phenomena or update those processes as needed.

Another criticism of many models concerns data requirements. Regression-type models, because of their simplicity in form, are often composed of few variables. This makes them attractive to potential users. The physical significance of each variable, however, or--more important--its relation to land-management activities is often questioned. Although the input to physical-process models may be more extensive than for other model types, each variable can be related to measurable characteristics of the drainage basin, thus avoiding many problems in interpreting the meaning of the different model variables. Recently, Simons et al. (1979a) have reported useful techniques for estimating input parameters from commonly gathered data. With such manuals, the field user can relate drainage-basin information and model parameters to provide the inputs needed to run models that would otherwise appear complex. Although inputs may need to be adjusted to reflect the judgment of the field user, model results using this approach will usually be adequate for planning. More detailed investigations will require a better defined and more accurate data set.

Physical-process models can and do avoid many of the concerns often expressed by potential users. If the model is linked in a modular format, it can be upgraded or adjusted to reflect the complexity or simplicity of the controlling physical processes. In addition, input variables to physical-process models can be more readily related to drainage-basin characteristics, and therefore management activities, than can variables for other types of models. All of these attributes make physical-process models more appealing for general use in drainage-basin studies.

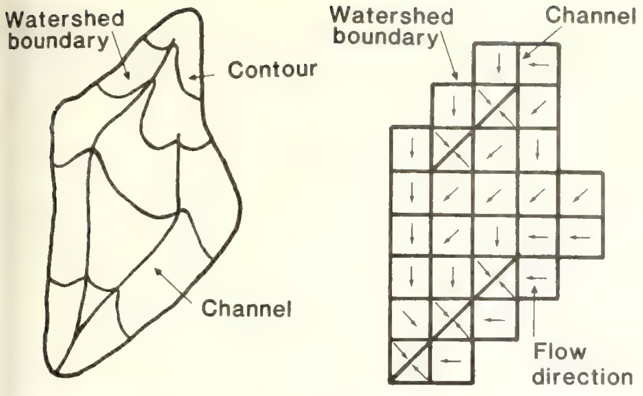
## SEDIMENT SOURCES IN DRAINAGE BASINS

Selection of an appropriate sediment-yield model is dependent upon the sources of sediment in the drainage basin. Components of the mathematical model must match the physical processes controlling the movement of water and sediment from the drainage basin. Four major sources of sediment i drainage basins are sheet and rill erosion, gullies, landslides, and channels (Simons et al. 1979b). Each of these natural sources can be modified by human activities. In addition, sediment sources are created by agricultural tillage, grazing of domestic animals, roadway construction and maintenance, timbering, mining, urbanization, and development of recreational land. Sheet-rill erosion and channel sources are probably best understood in terms of modeling. Gullying has been described by regression and physical-process models. Regression models usually relate gully growth to drainage area, soils, and precipitation (such as Thompson 1964). Physical-process approaches examine gully growth using processes of mass wasting and hydraulic transport (Bradford et al. 1973, Piest et al. 1975). Similarly, landslide sources have been described throughout the literature, but accurate quantitative models are still lacking. Mathematical descriptions of landslide sediment sources have been made by Ward (1976) and Simons et al. (1978a). More study is needed to estimate deliver of landslide-produced sediment to stream channels. Sediment in a drainage basin may be from a single type of source or a combination of types. The contribution from each source is often hard to identify without detailed field surveys. Sheet-rill and channel-erosion models will be the primary physical-process models until better mathematical descriptions of gullying and landsliding can be developed.

## FORMULATION OF PHYSICAL-PROCESS MATHEMATICAL MODEL

### Segmenting the Drainage Basin

Drainage-basin characteristics must be subdivided and digitized both spatially and temporally before they can be mathematically analyzed. Drainage-basin segmentation is spatial digitization (Simons et al. 1978b). Segmentation allows a drainage basin to be represented by single or multiple planar surfaces for the overland part and straight-line segments for the channel reaches (fig. 1). Segmenting the drainage basin allows computation of slope and azimuth of each planar surface and channel segment. The azimuth is then used to define flow direction and sequence to be used in flow computations. If data on vegetation type, soil type, canopy cover, and ground cover are available, they can be encoded at grid nodes to depict the spatial variation of these important factors. Such information is necessary in computing variations in water and sediment yields. Segmentation of the drainage basin can be as detailed as deemed necessary by the user. If information is required every 100 m, then the grid should be of a corresponding size. Some small drainage basins, however, may be represented by two planes and one channel.



**A. Topographic features** **B. Segmented watershed**

Figure 1.--Example of drainage-basin segmentation.

In addition to the above drainage-basin descriptors, channel cross-sectional geometry is usually represented by power relationships between parameters of wetted perimeter, flow area, top width, and depth.

Temporal subdivision takes place when precipitation and runoff are considered. Although rainfall and runoff are continuous processes, they must be divided into workable periods for analyses. This often depends on the size of drainage basin and the purpose of the model. If a long-term water balance is needed, periods of a day to a week may be adequate. If storm runoff from a small drainage basin is desired, rainfall and runoff periods from one to a few minutes may be required. Each use of the model and each drainage basin necessitate reevaluation of an appropriate time frame. Along these same lines, physical-process models can be used to estimate the response of drainage basins to rainfall and help determine a realistic sampling period for gaging installations and further model simulations.

Model Structure

Once drainage basin and other factors have been numerically defined by a segmentation procedure, the drainage basin can be modeled. Simons et al. (1975) developed a drainage-basin sediment model that is primarily applicable for surface-erosion simulation (fig. 2). It simulates surface flow and sediment production in small drainage basins. The basic framework of this model has been subsequently used to develop simplified and other models (e.g., Simons et al. 1977b, Simons et al. 1977d). The drainage basin is conceptually divided into the land-surface or overland-flow loop and a channel-system loop, each with different physical processes. The overland-flow loop simulates processes of interception, evaporation, infiltration, detachment of soil by impact of raindrops, erosion by overland flow, and overland water flow and sediment routing to the nearest channel. A channel-system loop determines water and sediment contributed by overland flow, which are routed in the channel, and the amount of channel erosion or sediment deposition throughout the channel system.

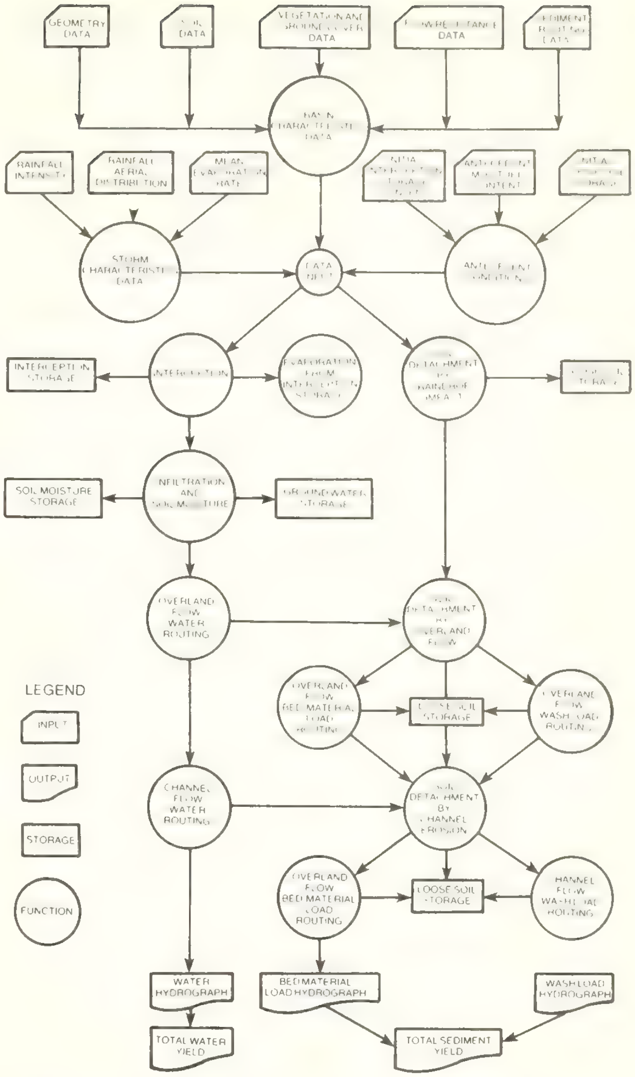


Figure 2.--Flow chart for the drainage-basin sediment and routing model.

Model Components

Rainfall excess is that amount of rainfall available for overland flow after all losses have been subtracted. Commonly considered losses are interception, depression storage, infiltration, and evapotranspiration. In storm-runoff simulation, losses from evapotranspiration are considered small and assumed negligible during the storm. Losses from depression storage can be combined into ground-cover interception. The two remaining losses are interception and infiltration.

The amount of interception loss depends on the percentage of the drainage-basin surface covered by canopy and ground cover, their respective water-holding capacities, and their initial moisture levels. The total intercepted volume can be written as

$$V_i = C_c V_c + C_g V_g \qquad (1)$$

in which $V_i$ is the total intercepted volume in depth, $C_c$ is the canopy-cover density ($0 \leq C_c \leq 1$), $V_c$ is the potential volume of canopy-cover interception in depth, $C_g$ is the ground-cover density ($0 \leq C_g \leq 1$), and $V_g$ is the potential volume of ground-cover interception in depth. The value of $V_i$ is dependent on the type of vegetation, height of vegetation (related to leaf areas), and the initial moisture level. The value of $V_g$ is a function of forest litter, grass, and the initial moisture level. Methods for estimating interception depths, as well as other variables, have been presented by Simons et al. (1979a).

As the model computations proceed through time, the rainfall is all intercepted until the potential volumes for ground and canopy cover are satisfied. This would constitute a series of net rainfall rates. Although interception losses are continuous over the storm period, the losses are assumed to occur during the beginning of the storm, and effective rainfall does not begin until the interception volume is satisfied.

The infiltration equation of Green and Ampt (1911) used in the drainage-basin model is a simple, physically based, two-parameter equation. It may be derived by direct application of Darcy's Law under the following assumptions: (1) a distinct piston wetting-front exists; (2) the hysteresis effects in the soil properties are negligible; and (3) the pressure effect of ponded water is negligible.

A Green-Ampt type equation may be written as

$$\frac{F}{\delta} - \ell n \left(1 + \frac{F}{\delta}\right) = \frac{Kt}{\delta} \qquad (2)$$

in which F is the infiltrated volume, K is the hydraulic conductivity of the soil in the wetted zone, t is the time, and $\delta$ is the potential head parameter and defined as

$$\delta = (\theta_w - \theta_i)\, \psi_{ave} \qquad (3)$$

in which $\theta_w$ is the moisture content of the soil after wetting, $\theta_i$ is the antecedent moisture content, and $\psi_{ave}$ is the average suction head across the wetting front.

If at any time, t, the infiltrated volume is F(t), then at some later time $t + \Delta t$

$$F(t + \Delta t) = F(t) + \Delta F \qquad (4)$$

in which $\Delta F$ is the change in infiltrated volume that occurred during the time increment $\Delta t$. An expression for $\Delta F$ is obtained from equation 4 as

$$\Delta F = F(t + \Delta t) - F(t) \quad . \qquad (5)$$

Li et al. (1976a) developed the following method of solving for the infiltration rate. Their derivation yields

$$\frac{\Delta F}{\delta} - \ell n \left[\frac{\delta + F(t) + \Delta F}{\delta + F(t)}\right] = \frac{K}{\delta}\, \Delta t \quad . \qquad (6)$$

Equation 6 is implicit with respect to $\Delta F$. The equation is simplified, however, by expanding the logarithmic term in a power series (Li et al. 1976c)

$$\ell n\left(1 + \frac{\Delta F}{\delta + F}\right) = \ell n\ 1 + \frac{\dfrac{2\Delta F}{\delta + F}}{2 + \dfrac{\Delta F}{\delta + F}} + \ldots \qquad (7)$$

Truncating equation 7 after the second term and substituting into equation 6 gives

$$\frac{\Delta F}{\delta} - 2 \left[\frac{\dfrac{\Delta F}{\delta + F}}{2 + \dfrac{\Delta F}{\delta + F}}\right] = \frac{K}{\delta}\, \Delta t \quad . \qquad (8)$$

Equation 8 is simplified into a quadratic with a solution of (Li et al. 1976a)

$$\Delta F = -\frac{(2F - \Delta K\ t)}{2} + \frac{[(2F - \Delta K\ t)^2 + 8K\Delta t(\delta + F)]^{1/2}}{2} \quad . \qquad (9)$$

Only the positive root of equation 9 has any physical significance. The average infiltration rate, $\bar{f}$, is obtained by dividing $\Delta F$ by $\Delta t$, or

$$\bar{f} = \frac{\Delta F}{\Delta t} \quad . \qquad (10)$$

After subtracting the interception and infiltration losses, the rainfall excess, $i_e$, can be determined. A rainfall event is commonly reported as an hyetograph, that is, a series of net rainfall intensities, I, each lasting for a time increment, $\Delta t$. Thus, if the net rainfall intensity is greater than the infiltration rate, the infiltration rate is subtracted from the net rainfall intensity to give the excess rainfall. If the net rainfall intensity is less than the corresponding infiltration rate, the infiltration rate equals the net rainfall intensity, and there is no excess.

### Water Routing

Water runoff can be described by the equation of continuity, the equation of motion, and equations describing resistance to flow.

Continuity Equation.--The equation of continuity for water is

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_\ell \qquad (11)$$

in which Q is the discharge, x is the downslope distance, A is the cross-sectional area of flow, t is time, and $q_\ell$ is lateral inflow or outflow rate per unit length of channel. For overland flow, $q_\ell$ is rainfall excess, A is depth of flow, and Q is the discharge per unit width of channel.

Momentum Equation.--The momentum equation for a prismatic channel can be expressed as (Henderson 1966)

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{1}{gA}\frac{\partial Q}{\partial t} - \frac{1}{gA}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) \qquad (12)$$

in which $S_f$ is the friction slope, $S_o$ is the channel bed slope, y is the depth of flow, and g is the gravitational acceleration.

The assumption of the kinematic wave approximation is that the friction slope is equal to the channel bed slope; that is, the gradients resulting from local and convective accelerations are assumed to be negligible, and the water-surface slope is assumed to be equal to the bed slope. Then the simplified momentum equation can be expressed as

$$S_o \approx S_f = f\,\frac{Q^2}{8gRA^2} \qquad (13)$$

in which f is the Darcy-Weisbach friction factor, and R is the hydraulic radius. By definition

$$R = \frac{A}{P} \qquad (14)$$

in which P is the wetted perimeter. Usually the wetted perimeter can be expressed as a power function of flow area

$$P = a_1 A^{b_1} \qquad (15)$$

where $a_1$ and $b_1$ are constants.

If Manning's equation is used, the simplified momentum equation is

$$S_o \approx S_f = \frac{n^2 Q^2}{2.21\, R^{4/3} A^2} \qquad (16)$$

in which n is Manning's roughness coefficient.

Resistance Equations.--In a natural drainage basin, form resistance from ground cover is a very important component of the resistance to flow. The dependence of flow resistance on ground cover becomes further complicated depending on whether or not the ground cover is submerged. Rarely is the ground cover submerged in overland-flow units, and only resistance caused by flow through ground cover is considered. In channel-flow units, the probability of submerging the ground cover is larger. The resistance is then considered as the resistance caused simultaneously by flow through and flow over ground cover.

Resistance to flow for the overland-flow response units is generally expressed as a function of surface-material type, vegetation type, and density of vegetation. Palmer (1946), Ree (1949), and Ree and Palmer (1949) conducted a series of experiments in channels with various types of grasses. More recently, Kouwen and Unny (1969), Phelps (1970), Wenzel (1970), Li and Shen (1973), and Chen (1976) carried the experimental studies further. Results indicate a functional relationship between the overal Darcy-Weisbach friction factor and flow characteristics as

$$f = \frac{K_t}{N_r} \qquad (17)$$

in which f is the overall Darcy-Weisbach friction coefficient, $N_r$ is the flow Reynolds number, and $K_t$ is a constant describing the overall resistance. According to Chen (1976), this type of relationship can be used for a Reynolds number up to 100,000. This would cover practically all of the possible overland-flow conditions on natural surfaces.

The flow Reynolds number is defined as

$$N_r = \frac{QR}{\nu A} \qquad (18)$$

in which $\nu$ is the kinematic viscosity of water.

Assuming that the factors describing resistance to flow are independent, the overall resistance can be expressed as

$$f = f_g + f_d \qquad (19)$$

in which $f_g$ is the Darcy-Weisbach friction factor for grain resistance only, which is a function of grain size, flow Reynolds number, and rainfall intensity, and $f_d$ is the Darcy-Weisbach friction factor resulting from form drag resistance, which is a function of ground-cover density, size of ground cover, drag coefficient, depth of flow, and flow Reynolds number. In overland-flow cases, the value of $f_g$ can be further assumed as

$$f_g = \frac{K_g}{N_r} \qquad (20)$$

in which $K_g$ is the parameter describing Darcy-Weisbach friction factor for grain resistance only. Laboratory experiments show that $K_g$ is between 30 and 60 (Chow 1959, Woolhiser 1975). $K_g$ is assumed to be about 45 to 50.

The overall overland-flow resistance can be assumed as a function of ground-cover density as

$$K_t = K_\ell + (K_h - K_\ell)\, C_g^2 \qquad (21)$$

in which $K_\ell$ is the parameter describing the minimum resistance ($C_g = 0.0$), and $K_h$ is the parameter describing the maximum resistance ($C_g = 1.0$).

In channel flow, the Darcy-Weisbach friction factor is often considered as a constant. Sometimes, the Chezy or Manning's equations are used in evaluating the overall resistance for overland flow and flow in rivers.

Relation of Discharge and Flow Area.--In general, the cross-sectional area of the flow can be expressed as a power function of discharge

$$A = \alpha Q^{\beta} \tag{22}$$

in which $\alpha$ and $\beta$ are coefficients whose values depend on the shape of the channel, the friction slope, and the roughness of the wetted perimeter.

If the Darcy-Weisbach friction factor is used, the values of $\alpha$ and $\beta$ can be determined by substituting equations 13, 14, 15, 17, and 18 into equation 22. The solutions are

$$\alpha = \left(\frac{K_t \nu a_1^2}{8 g S_f}\right)^{1/(3-2b_1)} \tag{23}$$

and

$$\beta = \frac{1}{3-2b_1} \tag{24}$$

For overland flows or flows in very wide channels, the wetted perimeter is constant, so that $b_1 = 0$ and $\beta = 1/3$. If Manning's and Chezy's equations are used, the corresponding $\alpha$ and $\beta$ values can similarly be determined.

The problem of water routing requires solving equations 11 and 22. These two equations can be solved either by an analytical method or a numerical method. The analytical solutions of equations 11 and 22 are available for some special cases (Eagleson 1970, Harley et al. 1970, Kibler and Woolhiser 1970, Li et al. 1975). They are not repeated here, but more detail can be found in Li (1979). Analytical approaches use the method of characteristics in x (distance) and t (time) space to describe water flow with no upslope inflows, only lateral inputs. Lateral inputs could be rainfall on planes or planes discharging into a channel. An analytical solution is desirable because no problem is encountered in computational stability and convergence. Unfortunately, the analytical solution is often restricted for practical applications because of the formulation of kinematic "shock." The shock is represented by the intersections of characteristics in the x-t plane. This produces an abrupt computational increase in flow depth (Kibler and Woolhiser 1970). Li et al. (1976b) give an indepth discussion of this limitation. For a small drainage basin with simple geometry having two planes and one channel, however, the above analytical procedure can be used. Simons et al. (1977a) report a simple drainage-basin model using small programmable calculations based on the two-planes and one-channel representation of drainage basins.

For the numerical solution, a nonlinear scheme was developed using an iterative procedure to solve a four-point implicit formulation of equations 11 and 22.[1] A linear scheme is used to obtain the initial estimate of the unknown discharge for the nonlinear scheme. The linear scheme may be used with no iterations to solve for the unknown discharge, providing the accuracy of the answer is satisfactory.

## Sediment Routing

The sediment-routing portion of the model is similar to the formulation used by Simons et al. (1975). The model is further developed to consider the routing of sediment by sizes, however. Increasing attention is being paid to routing sediment by sizes because different sizes of sediment have different uptake rates of other pollutants.

Movement of sediment from drainage basins is governed by the equation of continuity for sediment and sediment-transport equations. The amount of soil that could be transported is described by equations of sediment supply, which are the amount of soil detachment from raindrop impact and surface runoff. The equations used in the model are described below.

Continuity for Sediment.--The equation of continuity for sediment can be expressed as

$$\frac{\partial G_s}{\partial x} + \frac{\partial CA}{\partial t} + (1-\lambda)\frac{\partial PZ}{\partial t} = g_s \tag{25}$$

in which

$$C = \frac{G_s}{Q} \tag{26}$$

and $G_s$ is the total sediment-transport rate by volume per unit time, C is the sediment concentration by volume, Z is the depth of loose soil, $\lambda$ is the soil porosity, P is the wetted perimeter, and $g_s$ is the lateral sediment inflow.

Sediment load can be subdivided into different sizes, and the continuity equation can be solved for N parts as

$$\frac{\partial G_{si}}{\partial x} + \frac{\partial C_i A}{\partial t} + (1-\lambda)\frac{\partial PZ_i}{\partial t} = g_{si} \tag{27}$$

$$i = 1, \ldots, N$$

where i is the size-fraction index and N is the number of size fractions. The other terms are related to the individual size fractions as

$$C_i = \frac{G_{si}}{Q} \tag{28}$$

$$C = \sum_{i=1}^{N} C_i \tag{29}$$

and

$$Z = \sum_{i=1}^{N} Z_i \tag{30}$$

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[1] Li, R. M., R. K. Simons, and D. B. Simons. A generalized kinematic wave approximation for floodrouting. Submitted to Am. Soc. Civ. Eng. Hydraul. Div. for possible publication.

Sediment-Transport Equations.--Sediment-transport equations are used to determine transport capacity of a specific flow condition. Different transport capacities can be expected for different sediment sizes. For each sediment size, the transport rate includes the bedload-transport rate and the suspended-load transport rate.

The Meyer-Peter, Müller equation is a simple and commonly used bedload-transport equation (U.S. Bureau of Reclamation 1960). It is

$$q_b = \frac{12.85}{\sqrt{\rho}\ \gamma_s} (\tau_o - \tau_c)^{1.5} \qquad (31)$$

in which

$$\tau_c = \delta_s (\gamma_s - \gamma)\, d_s \quad . \qquad (32)$$

Here, $q_b$ is the bedload transport rate in volume per unit width for a specific size of sediment, $\tau_o$ is the boundary shear stress acting on the grain, $\tau_c$ is the critical tractive force, $\rho$ is the density of water, $\gamma_s$ is the specific weight of sediment, $\gamma$ is the specific weight of water, $d_s$ is the size of sediment, and $\delta_s$ is usually 0.047 for most flow conditions (Gessler 1965). If rilling develops on the overland-flow surface, the value of $\delta_s$ should be lower.

The Meyer-Peter, Müller equation is not necessary, but an equation should be chosen that is applicable to field conditions. Other bedload-transport equations follow a form similar to equation 31.

The flow discharge, Q, and flow area, A, are determined in time and space by the water-routing procedure previously described. The corresponding value of $\tau_o$ is computed as follows. If the mean flow velocity is

$$V = Q/A \quad , \qquad (33)$$

then the boundary shear stress acting on the grain (using equation 20) is

$$\tau_o = \frac{1}{8} \rho f_g V^2 = \frac{1}{8} \rho \frac{K_g}{N_r} V^2 \quad . \qquad (34)$$

A commonly used and theoretically sound method for estimating suspended load was presented by Einstein (1950). Other methods are available, but the Einstein method has been found acceptable in many modeling applications.

The suspended-sediment concentration profile relating sediment concentration with depth above the bed (Einstein 1950) can be written as

$$\frac{C_\xi}{C_a} = \left(\frac{R-\xi}{\xi} \frac{a'}{R-a'}\right)^w \qquad (35)$$

in which $C_\xi$ is the sediment concentration at the distance $\xi$ from the bed, $C_a$ is the concentration at a distance a' above the bed, and w is a parameter defined as

$$w = \frac{V_s}{\kappa U_*} \qquad (36)$$

where $V_s$ is the settling velocity of the sediment particles, $\kappa$ is the von Karman constant (assumed 0.4), and $U_*$ is the shear velocity of the flow defined as

$$U_* = \left(\frac{\tau_*}{\rho}\right)^{1/2} \quad . \qquad (37)$$

Note that

$$\tau_* = \frac{1}{8} f \rho V^2 \qquad (38)$$

where f is the overall Darcy-Weisbach resistance factor previously described.

A logarithmic-velocity profile is commonly adopted to describe the vertical velocity distribution in turbulent flows such as

$$\frac{u_\xi}{U_*} = B + 2.5\, \ell n \left(\frac{\xi}{\eta_s}\right) \qquad (39)$$

in which $u_\xi$ is the point mean velocity at the distance $\xi$ from the bed, B is a constant dependent on roughness, and $\eta_s$ is the roughness height.

The integral of suspended-sediment load above the a' level in the flow is obtained by combining equations 35 and 39 or

$$q_s = \int_{a'}^{R} u_\xi C_\xi\, d\xi = C_a U_* \int_{a'}^{R} \left[B + 2.5\, \ell n \left(\frac{\xi}{\eta_s}\right)\right] \left(\frac{R-\xi}{\xi} \frac{a'}{R-a'}\right)^w d\xi \qquad (40)$$

substituting

$$\sigma = \frac{\xi}{R} \qquad (41)$$

and

$$G = \frac{a'}{R} \qquad (42)$$

results in

$$q_s = C_a U_* a' \frac{G^{w-1}}{(1-G)^w} \left\{ \left[B + 2.5\, \ell n \left(\frac{R}{\eta_s}\right)\right] \int_G^1 \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma + 2.5 \int_G^1 \ell n \sigma \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma \right\} \quad . \qquad (43)$$

According to Einstein (1950), the concentration near the "bed layer," $C_a$, is related to the bedload transport rate, $q_b$, by the expression

$$q_b = 11.6\, C_a U_* a' \qquad (44)$$

in which a' is defined as the thickness of the bed layer or twice the size of a representative sediment particle.

The average flow velocity, V, is defined by the equation

$$V = \frac{\int_0^R u_\xi \, d\xi}{\int_0^R d\xi} \qquad (45)$$

Using equation 39

$$\frac{V}{U_*} = B + 2.5 \, \ell n\left(\frac{R}{\eta_s}\right) - 2.5 \qquad (46)$$

Einstein (1950) defined the two integrals in equation 43 as

$$I_1 = \int_G^1 \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma \qquad (47)$$

and

$$I_2 = \int_G^1 \left(\frac{1-\sigma}{\sigma}\right)^w \ell n\sigma \, d\sigma \qquad (48)$$

The integrals, $I_1$ and $I_2$, cannot be integrated in closed form for most values of w, so a numerical integration is necessary. An efficient numerical method of determining $I_1$ and $I_2$ in the model was developed by Li (1974).

The substitution of equations 44, 46, 47, and 48 into equation 43 yields

$$q_s = \frac{q_b}{11.6} \frac{G^{w-1}}{(1-G)^w} \left[\left(\frac{V}{U_*} + 2.5\right) I_1 + 2.5 \, I_2\right] \qquad (49)$$

The total bed-material transport per unit width of channel is

$$q_t = q_b + q_s \qquad (50)$$

Equation 50 gives the total bed-material transport per unit width of channel for a uniform size of sediment in the bed. When transport by different sizes and the entire width of channel are considered, the sediment-transport capacity of the ith size fraction of a sediment mixture would be

$$G_{ci} = P \, F_{ai} \, q_t \qquad (51)$$

in which $G_{ci}$ is the sediment-transport capacity for the ith size, and $F_{ai}$ is the adjusted fraction of the ith size sediment, which is determined in the next section.

Equations for Sediment Supply.--The sediment-supply rate is another determining factor in the actual sediment-transport rate. Simons et al. (1975) stated that the sediment supply depends on the initial depth of loose soil left from previous storms, the amount of soil detachment by raindrop impact, and the amount of soil detachment by flow.

Soil Detachment by Raindrop Impact.--Raindrop impact is a primary source of kinetic energy for detaching soil from any unprotected land surface. Ellison (1944) made a comprehensive study of raindrop splash. Laws and Parson (1943), Mutchle (1967), and Young and Wiersma (1973) contributed to the study of detachment by raindrop impact. The conclusion drawn from these studies is that soil detachment is a function of erosivity of rainfall and the erodibility of the soil particles. The erosivity is directly related to the energy produced by raindrop impact and is generally formulated as a power function of rainfall intensity, size of droplet, cover condition, and terminal velocity of the drop. Carter et al. (1974) reported that energy produce by raindrop impact is also a function of air temperature, season of the year, and storm duration. In the model, the potential rate of soil detachment by raindrop impact in inches per hour is assumed as a power function of rainfall intensity as given by Meyer (1971)

$$D_r = a_5 I^{b_5} \left(1 - \frac{Z_w}{Z_m}\right)(1-C_g)(1-C_c) \qquad (52)$$

in which I is the rainfall intensity, $a_5$ is a parameter depending on soil characteristics, and $b_5$ is a constant ($b_5 = 2.0$, Meyer (1971)). The term $Z_w$ is the depth of water plus the loose soil. The term $Z_m$ is the maximum penetration depth of raindrop splash. According to Mutchler and Young (1975), $Z_m$ can be equal to three times the median raindrop size. The median raindrop size is often expressed as a power function of rainfall intensity, I. Therefore, $Z_m$ can be written as

$$Z_m = 3(2.23 \, I^{0.182}) \qquad (53)$$

in which $Z_m$ is in millimeters.

Equation 52 is valid when $Z_w$ is less than $Z_m$. When the depth of loose soils plus the water depth is greater than $Z_m$, $D_r$ is zero; that is,

$$D_r = 0, \text{ if } Z_w > Z_m \qquad (54)$$

If trees are very tall, the drops from leaves can regain terminal velocity and have the same erosive potential. Ground-cover density under trees is usually very high, however, thus protecting the surface. The canopy-cover density, $C_g$, in equation 52 should be the portion that can protect the surface effectively from raindrop impact.

The potential rate of loose-soil detachment, $D_r$, is expressed in units of depth per unit time. Thus, the new amount of loose soil available for transport is

$$Z_{i\,New} = Z_{i\,Old} + F_i \, D_r \, \Delta t \qquad (55)$$

where $Z_i$ is the amount of loose soil available and $F_i$ is the original percentage of sediment in a given size fraction designated by i.

The percentage in each size fraction on the surface changes over time because of armoring. Water transports the smaller sizes of sediment more easily and leaves larger sized fractions behind. Thus, the percentages of surface material need adjustment at each time step. If the total depth of loose soil is greater than $D_a$ (the thickness of the armor layer), the adjusted percentages, $F_{ai}$, can be written as

$$F_{ai} = \frac{Z_i}{Z} \quad . \tag{56}$$

If the total loose-soil depth, Z, is less than $D_a$, the adjusted percentages must account for the layer of undisturbed soil that is distributed according to the original percentages plus the loose soil that covers it,

$$F_{ai} = \frac{1}{D_a} [Z_i + F_i (D_a - Z)] \quad . \tag{57}$$

The thickness of the armor layer can be determined as the maximum size of particles in motion. The size of sediment for which 84 percent of the sample is finer by weight, $D_{84}$, is usually assumed to be representative of the armor layer.

Soil Detachment by Surface Runoff.--The amount of soil detachment by surface runoff is determined by comparing the total sediment-transport capacity to the total available amount of loose soil. The total sediment-transport capacity is

$$G_c = \sum_{i=1}^{N} G_{ci} \quad . \tag{58}$$

By substituting the total sediment-transport capacity, $G_c$, into the transport rate in equation 25, the total potential change in loose soil, $Z^P$, can be determined as

$$\Delta Z^P = \frac{\partial Z}{\partial t} \Delta t \quad . \tag{59}$$

If $\Delta Z^P > -Z$ (that is, positive aggradation or negative degradation is less than Z), the loose-soil storage is enough for transport and no detachment of soil by surface runoff is expected. Soil is detached if $\Delta Z^P < -Z$, and the amount of detachment is

$$D = -D_f \; \Delta Z^P + Z] \tag{60}$$

in which D is the total amount of detached soil and $D_f$ is defined as a detachment coefficient with values ranging from 0.0 to 1.0 depending on soil erodibility. As an example, if the flow were over a nonerodible surface such as gravel, the value for $D_f$ would be zero. If the flow were in a river where the riverbed is always loose and available for transport, the value for $D_f$ would be unity.

The new amount of loose soil should be further modified as

$$Z_{i_{\text{Total}}} = Z_{i_{\text{New}}} + D \, F_i \tag{61}$$

in which $Z_i$ is calculated for each size fraction of sediment.

Numerical Procedure for Sediment Routing.--Similar to the water-routing scheme in its finite difference structure, the numerical routing of sediment by sizes allows a constant check on continuity at each time and space point. This constant mass balance permits tracking of aggradation and degradation on the land surface and in stream channels. Such information defines lateral loadings to stream channels from overland flow. Channel segments where storage or scour is occurring can be delineated to help in defining the movement of sediment. Segments with excessive aggradation or degradation indicate areas where fisheries may be harmed. The movement and storage of sediment is particularly useful in relating land-use activities to sediment yields. Channel storage will sometimes mask actual increases in sediment production until a runoff event of significant magnitude "flushes" the stored material. By numerical routing, storage areas and the size of the "flushing" event can be determined.

## APPLICATIONS OF METHODOLOGY

The methodology presented in the previous sections has been used to develop numerous physical-process models that estimate water and sediment yields from land surfaces, roadways, and drainage basins. The abundance of models precludes inclusion of all of them in this paper.

Instead, a single drainage-basin application is presented with a description of the approach used in parameter estimation and model adjustment. Two levels of models are used. One is a complex geometry, finite-difference routing scheme (Simons et al. 1975), and the other is a simplified geometry, analytical routing scheme (Simons et al. 1977c). Watershed 17 in the Beaver Creek Experimental Forest near Flagstaff, Arizona, was chosen for application because of its relatively good data base and because it is characterized by surface runoff and erosion. The drainage basin is fairly flat, with most slopes less than about 10 percent. Total area is 116.3 ha. Soils are stony clays, silt loams, and stony silt loams. Saturated hydraulic conductivities are about 1.3 mm/hour. Ground cover is about 34 percent, and canopy cover is about 10 percent. Interception values as derived from Zinke (1965) are estimated at 2.5 mm for ground cover and about 7.5 mm for the canopy. The minimum-resistance parameter estimated for a gravel surface is 500 and the maximum estimated is about 42,000. These values provide a reasonable calibrated flow resistance for the ground-cover conditions in the area. Manning's n for the channel is estimated at about 0.05.

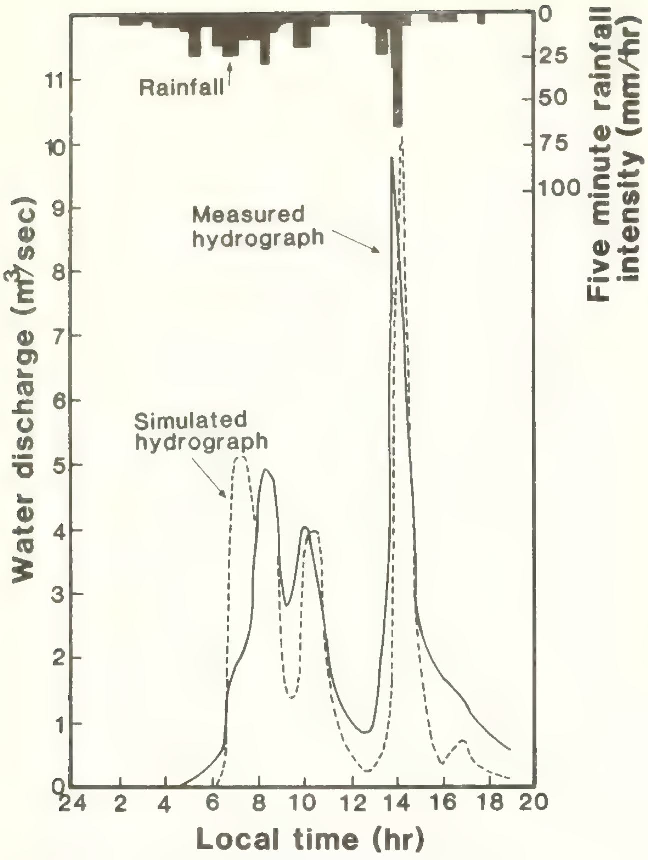

Figure 3.--Water hydrograph from Watershed 17 for the September 5, 1970 storm (after Simons et al. 1975).

The model was calibrated with four parameters and one storm on Watershed 17. The storm was on Labor Day, September 5, 1970. Initial moisture content was varied within reasonable limits for field conditions to match runoff volume, and overland-flow resistance was varied to match timing of the peaks; the rainfall-detachment coefficient, $a_5$, and overland-flow detachment coefficients, $D_f$, were adjusted to account for the measured sediment yields. The $a_5$ coefficient is closely related to and adjusted by considering the fine fraction of the yield, and $D_f$ can be adjusted with respect to the total yield. The results obtained by the water calibration, using the initial moisture conditions and flow resistance, are shown in figure 3. Simulated and measured hydrographs match well. Simulated sediment yield for the storm was within 15 percent of measured values.

The parameters from Watershed 17 were then used in predicting the response of a nearby 127-ha drainage basin, Watershed 1, to five rainfall storms. Watershed 1 is a little steeper than Watershed 17 but had been clearcut so that canopy cover was zero. Other parameters related to soils and flow resistance are similar for both drainage basins. The model was used to simulate outflow hydrographs and sediment yields for five storms from Watershed 1. The only variable that was adjusted between the storms was the antecedent moisture. All other variables remained the same. Table 1 lists the results of the simulations as compared to the measured values for the water hydrographs. Only two sediment-yield values were available, and both of those were predicted within 25 percent.

Table 1--Errors in simulation

| Storm | Measured surface runoff | Percentage difference between simulated and measured values | | |
|---|---|---|---|---|
| | | Water yield | Peak flow | Time to peak |
| | Millimeters | | | |
| WATERSHED 17 | | | | |
| Sept. 5, 1970 (calibration storm) | 101 | -14.6 | +11.4 | +2.1 |
| WATERSHED 1 | | | | |
| Sept. 5, 1970 | 41.7 | +12.9 | -0.2 | -3.1 |
| Sept. 6, 1967 | 0.76 | +7.2 | -7.7 | +6.7 |
| Nov. 22, 1965 | 2.79 | +1.3 | -0.4 | +2.1 |
| Nov. 24, 1965 | 2.03 | -23.7 | +31.0 | -7.7 |
| Nov. 25, 1965 | 6.10 | -23.2 | +23.6 | -6.3 |

The good agreement between the predicted and measured values obtained by only adjusting a single model parameter indicates the transferability of this model from one drainage basin to another with a minimum of recalibration. This occurs because the model adequately simulated the controlling physical processes of overland-flow and surface-erosion characteristics of the drainage basin. If the physical processes had been different, the model would not be applicable.

## Application of Simplified Water- and Sediment-Yield Model to Watershed 17

In this example, the water- and sediment-yield model (SEDWAT) developed by Simons et al. (1977c) is used to assess changes in streamflow and sediment yield resulting from different drainage-basin practices. In SEDWAT, drainage-basin geometry is represented by two planes and one channel, and water is analytically routed. Simulated practices are mechanical site preparation, timber harvesting, and grazing. Watershed 17 is chosen for use in these hypothetical examples. The base event was the storm of September 5, 1970. Peak recorded discharge was about 9.77 cm, and runoff volume was about 101 mm. Sediment production was 0.67 t/ha. Using the same data base and similar calibation, model simulations produced a peak of 10.27 cm, a water yield of 5.25 mm, and sediment yield was again 0.67 t/ha. All three of these simulated values are quite good because the controlling processes are correctly incorporated in the simplified model. Because the simulated and measured responses are comparable, the simulated results will be used as initial or baseline conditions.

To demonstrate the use of physical-process models for analyzing future management activities, four planning alternatives were simulated.

### Alternative 1. Mechanical Site Preparation

The major modification to the drainage basin is compaction of the soil. The percent of area with ground and canopy remains the same, but the hydraulic conductivity is reduced to 0.25 mm/hour over the entire drainage basin (table 2). The simulated sediment yield is what would be expected after the loose material has been flushed out of the system during an earlier storm (table 3); that is, the sediment-detachment coefficients have not been changed.

### Alternative 2. Removal of Canopy Cover

Although economical, clearcutting may be accompanied by high rates of erosion and subsequently higher yields of sediment, depending on the field conditions. The increase in sediment yield in this case is simulated by combining the effects of mechanical site preparation from alternative 1 with removal of all canopy cover. The hydraulic conductivity is again 0.25 mm/hour, and the percent of area covered by ground cover and canopy cover is set to zero (table 2). A ground cover of zero is extreme and is used here for comparative purposes.

Table 2--Parameters used in SEDWAT simulation of management alternatives

| | Baseline and alternative parameters | | |
|---|---|---|---|
| Alternative | Hydraulic conductivity | Canopy cover | Ground cover |
| | mm/hour | -------Percent-------- | |
| Baseline condition | 1.27 | 10 | 34 |
| 1 | .25 | 10 | 34 |
| 2 | .25 | 0 | 0 |
| 3 | 1.02 | 0 | 17 |
| 4 | .76 | 10 | 0 |

Table 3--Simulated drainage-basin responses using SEDWAT for four land-use alternatives. Baseline conditions: peak discharge = 10.27 $m^3$/second, water yield = 95.25 mm, sediment production = 0.67 t/ha.

| | Ratio of simulated result to baseline condition | | |
|---|---|---|---|
| Alternative | Peak discharge | Water yield | Sediment production |
| 1 | 1.17 | 1.21 | 1.06 |
| 2 | 1.17 | 1.21 | 3.25 |
| 3 | 1.13 | 1.04 | 1.62 |
| 4 | 1.15 | 1.09 | 2.79 |

### Alternative 3. Removal of Trees with Less Ground Disturbance

If care is taken to minimize the disturbance of ground cover, the canopy can be removed with a considerably lower sediment yield (table 3). This may be seen by reducing the ground-cover percent to half the original and the hydraulic conductivity to 1.02 mm/hour (table 2). The canopy is completely removed.

### Alternative 4. Overgrazing

Livestock or large populations of native animals can often cause severe damage to the ground cover by overgrazing. The effects of overgrazing can be included in the model by simulated removal of the ground cover and reduction of the hydraulic conductivity through compaction caused by trampling. In this example, the conductivity is reduced to 0.76 mm/hour and the ground cover is zero (table 2).

These alternatives are summarized in table 2. The results of model simulation of the baseline condition and all four alternatives are listed in table 3. Obviously, land-use alternative 2 creates conditions allowing the highest production of sediment. In every alternative, the peak discharge was increased, primarily because of a drop in hydraulic conductivity and partially from a decrease in flow resistance. Water yield also increased in every alternative because of decreases in interception and infiltration.

Table 4--Simulated sediment-water concentration for four land-use alternatives

| Alternative | Concentration of sediment in mixture | |
|---|---|---|
| | Parts per million | Ratio to baseline |
| Baseline conditions | 706 | 1.00 |
| 1 | 619 | .88 |
| 2 | 1897 | 2.69 |
| 3 | 1100 | 1.56 |
| 4 | 1808 | 2.56 |

The relative effects of each alternative can also be compared in terms of average concentration of the sediment-water mixture (table 4). These comparisons represent a key point for assessing management alternatives. If increases in water and sediment yields are primary criteria, alternative 2 would be the worst; however, if sediment concentration is used, alternative 4 is just as undesirable (table 4).

Note that the parameters chosen in all of these examples reflect particular responses to land use. These numbers were arbitrarily chosen and could reflect, in some instances, the most severe impact. One of the strengths of using a physical-process simulation model is that effects of different levels of land use may be examined.

Numbers generated from the simulations can be compared as relative ratios or marginal values. Effects of land-use alternatives can then be discussed in terms of percentage increase or decrease. Simultaneously, the absolute simulated values can be checked to see if they are physically realistic and, if so, useful as water-quality indicators.

Planning decisions based on state-of-the-science techniques such as mathematical models have two other attributes. First, they quantify drainage-basin response in a manner that can be readily related to measurable drainage-basin characteristics. Second, they are becoming accepted as the best method for determining system response to drainage-basin change. These two reasons alone indicate that mathematical modeling will become, by necessity, a widely used technique in estimating water and sediment yields from forested drainage basins.

## SUMMARY AND CONCLUSIONS

Mathematical models based on physical processes governing runoff and sediment yield from drainage basins can be developed and used for a variety of purposes. The key is correct simulation of the controlling processes in the chosen drainage basin. If properly formulated and documented, models can be a valuable aid to forest managers. When correctly applied, physical-process models can provide insights into the movement of water and sediment within and from drainage basins for initial and disturbed conditions. This paper has attempted to bridge gaps between model builders and field users to show the applicability and utility of physical-process models.

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# Sedimentation in the Chaparral: How Do You Handle Unusual Events?

Raymond M. Rice

## ABSTRACT

Processes of erosion and sedimentation in steep chaparral drainage basins of southern California are described. The word "hyperschedastic" is coined to describe the sedimentation regime which is highly variable because of the interaction of marginally stable drainage basins, great variability in storm inputs, and the random occurrence of brush fires.

The difficulties and advantages of describing chaparral sedimentation using either empiric or process models are dicussed. Modeling based on Monte Carlo simulation is suggested as a way of capturing many of the benefits of empiric and process models.

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Raymond M. Rice, Principal Hydrologist, Pacific Southwest Forest and Range Experiment Station, Redwood Sciences Laboratory, Arcata, California 95521.

## INTRODUCTION

Processes of erosion and sedimentation in steep chaparral drainage basins in southern California are described, as the basis of a wider discussion of sediment budgets, sediment routing, and drainage-basin modeling in general. A simulation approach to sediment budgets and sediment routing is proposed which incorporates some desirable features of process models and empiric models.

## THE CHAPARRAL ENVIRONMENT

Chaparral occurs in a wide variety of environments. This discussion treats a narrower range of conditions occurring in the steep "front country" drainage basins of the San Gabriel and San Bernardino Mountains in the Transverse Range in southern California. These drainage basins present the greatest flood and management problems, and this limitation in scope permits a sharper definition of relationships than would be possible in a more general discussion.

### Climate

Chaparral grows in a Mediterranean climate. In southern California, most chaparral stands receive between 400 and 700 mm of rain annually with about three-quarters of the precipitation falling during December through March. Rainfall varies greatly from year to year. In Glendora, rain in the wettest year of a 97-year record was over seven times that in the driest year (fig. 1). Winter temperatures average 9°C. The summer months average about 20°C and are normally without rain. Fire is favored by severe heat waves, accompanied by humidities of 15 to 20 percent, which occur several times each season. Maximum temperatures during these heat waves are typically around 40°C. Another fire-promoting element of the climate is the strong, desiccating, foehn winds that occur most frequently from mid-September through December. Chaparral vegetation has evolved in response to repeated fire and great annual and seasonal variations in moisture availability and evaporative stress.

### Geology and Topography

The eastern portion of the Transverse Range is mainly underlain by Precambrian to Cretaceous igneous and metamorphic rocks; to the west, Cenozoic sedimentary formations predominate (California Division of Mines and Geology 1969). In both areas, poorly developed, coarse-textured, erodible soils are the rule. Soil depths average about 60 cm, but depth is of little hydrologic importance because the parent material is typicall so weathered or fractured that for a depth of 1 to 3 m its ability to store and transmit water is little different from the overlying soil (Krammes 1967). As a consequence, chaparral drainage basins normally have a thick, hydrologically active mantle.

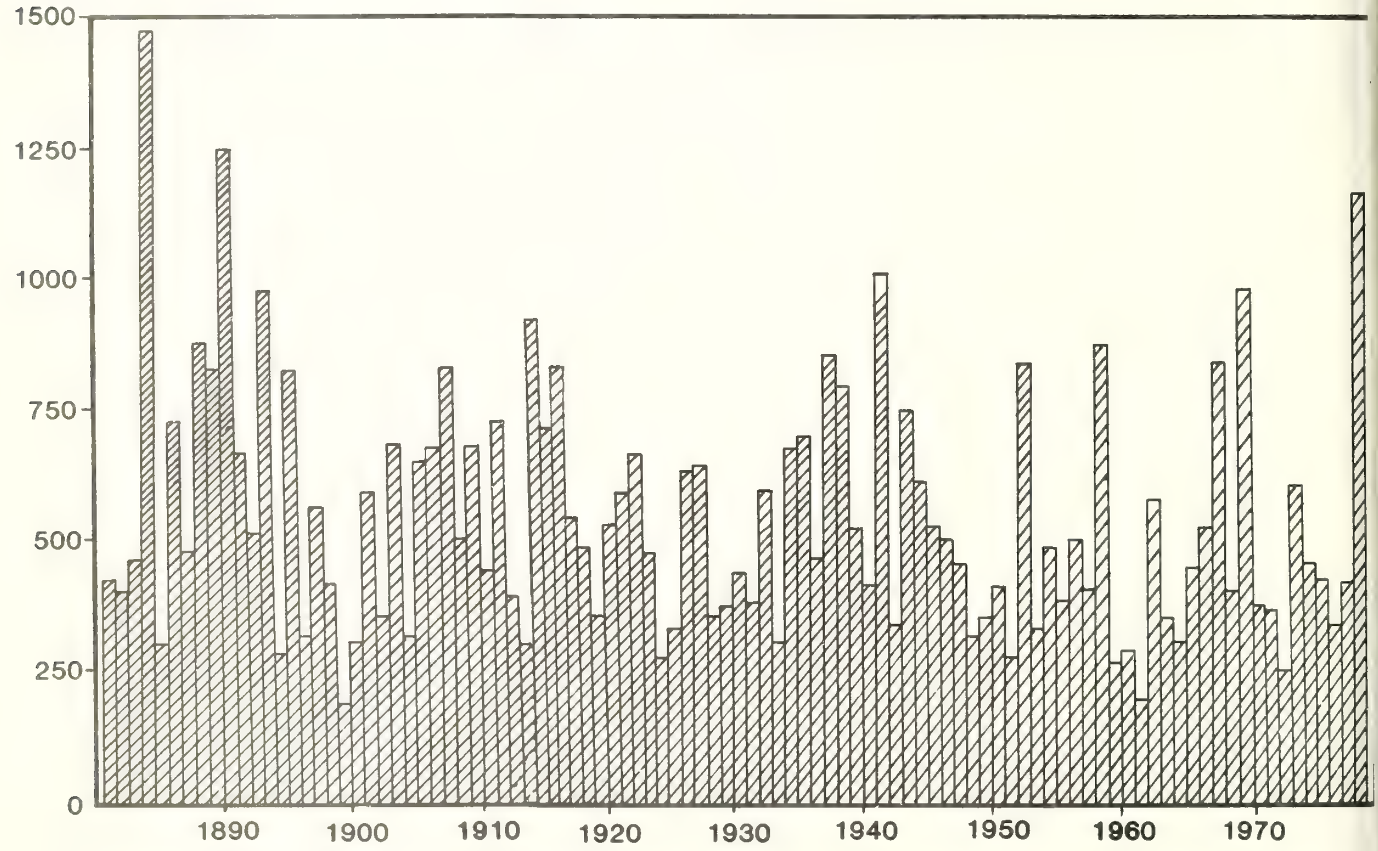

Figure 1.--Annual rainfall in the West rain gage. Glendora, California.

The mountains of the Transverse and Coast Ranges are currently being uplifted at a rate of about 60 cm a century (Scott and Williams 1974). This rapid uplift has rejuvenated the drainage system, producing average channel gradients of about 15 percent and average hillslope gradients of about 60 percent. The steep gradients cause the hillslopes to be very efficient at delivering soil to the stream channels, and the channels can also move large amounts of sediment if flows are high enough.

### Vegetation

Chaparral plants are adapted to the Mediterranean climate and to the associated fires. Adaptations to drought, such as leaf morphology and the accumulation of extractive compounds in chaparral, contribute to high flammability. Because the plant community is specialized for postfire regeneration, the vegetative and hydrologic recovery of chaparral drainage basins is rapid after fire. As a result of rapid vegetative regrowth, Kittredge (1939) found that, 17 years after a fire, litter accumulation was 13 t/ha and, in an area not burned for over 50 years, the accumulation was 37 t/ha. This litter accumulation protects the soil surface, increases its roughness, and temporarily stores rain falling at rates greater than the infiltration rate. These actions insure that surface erosion and overland flow rarely occur.

### Fire

Ecological evidence suggests that fire has played a prominent role in chaparral communities for millions of years. Keeley (1977) proposes that the existence of the genera Arctostaphylos and Ceanothus, the majority of whose species do not sprout, indicates that the interfire interval formerly may have been longer than it is now. He calls this the "Stochastic-Fire Hypothesis." He argues that because lightning fires in southern California occur mainly in summer and mainly at high elevations in the interior portions of the mountain ranges, for most of the chaparral to be ignited by lightning would be difficult. He suggests that relatively few lightning fires would continue to burn long enough to be swept downslope and coastward by the autumn foehn winds. Aschmann (1977) believes that increased fire frequency resulted both from accidental and purposeful burning on the part of aborigines. Preliminary analyses of varved cores taken from the Santa Barbara basin support this idea (Byrne et al. 1977). That record indicated that very large fires may have occured every 20 to 40 years. A 150-year core taken from the 16th and 17th centuries showed considerably more variability in charcoal concentrations than one spanning the 40 years between 1931 and 1970. This suggests the hypothesis that the greater temporal and areal homogeneity of modern fire occurrence is a result of the population increase.

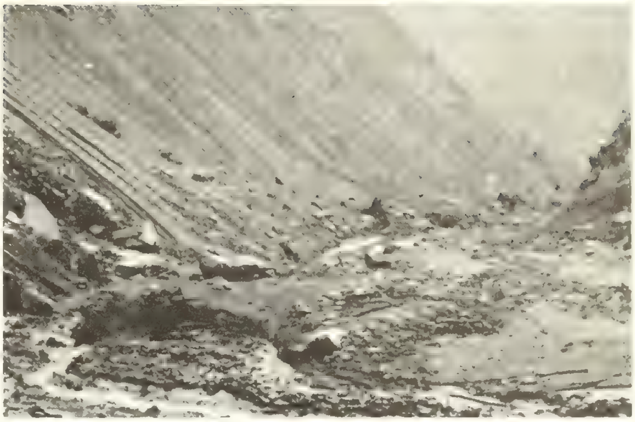

Figure 2.--Dry-ravel deposits which had been blocking channel of Monroe Canyon are eroded by storm of October 9-10, 1960.

## EROSIONAL PROCESSES

### Dry Ravel

Dry ravel is the most ubiquitous erosional process occurring in the chaparral. This process, sometimes termed "dry creep" (Krammes 1965), is the downslope movement by gravity of individual grains or aggregates of soil. The slope threshold for dry ravel is about 30 degrees. Kittredge (1939) estimated that dry ravel occurred on about 17 percent of his study area. My own inventory of the chaparral zone of southern California indicates that about 25 percent of the area is subject to dry ravel. The proportion of the front-country drainage basins that are steep enough for dry ravel is higher. In Englewild Canyon above Glendora, 40 percent of the slopes are steeper than 30 degrees. Englewild has gentler topography than the majority of the front-country drainage basins. Therefore, about two-thirds of the slopes of front-country drainage basins are probably steep enough for dry ravel.

Dry ravel is initiated by many types of small disturbances. Small sand runs can start when deer, small rodents, and even birds walk on a slope. One of the principal triggers, however, seems to be the movement of vegetation during periods of strong foehn winds. Five years of monitoring the Arroyo Seco drainage showed an average dry-season erosion rate of 0.96 $m^3$/ha, which was 55 percent of the total surface erosion measured (Anderson et al. 1959). Later studies of postfire erosion revealed that about half of the wet-season erosion was actually dry ravel occurring between winter rainstorms (Krammes and Osborne 1969). Consequently, I believe that, with unburned chaparral, the dry-ravel rate is about 1.4 $m^3$/ha per year. In the autumn of 1959, a wild fire swept over the Arroyo Seco study area resulting in about 39 $m^3$/ha of dry-ravel erosion during the next 3 months. The immediate effect of fire on dry ravel is to consume the forest litter that has been serving as temporary barriers to the downslope movement. Accelerated ravel occurs within minutes of the passage of the fire and can produce debris cones blocking stream channels within a few hours (fig. 2). Fire also accelerates dry ravel by the creation of a water-repellent layer (DeBano 1969). The waterrepellent layer traps precipitation in the surface soil where it is more easily evaporated. In addition to reducing percolation, it also prevents the capillary rise of water to the surface from deeper soil strata. By inhibiting the vertical movement of water, the water-repellent layer causes the soil surface to dry more quickly between storms and, therefore, to be subject to dry ravel for a greater portion of the wet season. Although fire-related water repellency is detectable for a long time, it ceases to affect runoff or erosion significantly within 2 or 3 years after a fire.

### Surface Erosion by Flowing Water

Surface erosion is a rarity in unburned chaparral drainage basins because litter usually protects the soil surface. Even without that protection, the thick, hydrologically active mantle can store and transmit large volumes of water. Furthermore, rainfall intensities rarely exceed infiltration rates. In none of the 300 largest storms during 24 years on the San Dimas Experimental Forest did the rainfall rate exceed the average hydraulic conductivity of the soil for 1 hour; in only 1 percent of the storms was it exceeded for 30 minutes (Reimann and Hamilton 1959). In all, only about 2.5 percent of the precipitation fell at a rate higher than the infiltration rate of the soil, and some of this rain was dispersed in time so that it had little effect on runoff. Both Colman (1953) and Troxell (1953) reported that almost no overland flow occurred during the flood of 1938. During that storm, less than 1 percent of the precipitation was measured as surface runoff from research plots, even though the streamflow from various drainage basins amounted to 16 to 38 percent of storm precipitation. Surface erosion remains almost nil without the transporting medium of overland flow, even though some minor erosion may result from drop impact of rainfall or throughfall.

The passage of a fire through chaparral usually greatly increases surface erosion by altering hillslope hydrology. A water-repellent layer is often created. This layer presents a relatively impervious barrier to deeper percolation. As a result, a drainage basin that might have a hydrologically active mantle 2 m thick when unburned may have its effective thickness reduced by fire to a few centimeters (Krammes and Osborne 1969). A recently burned slope can become "saturated" by just a few centimeters of precipitation.

Characteristically, dry ravel after fire accumulates during summer and fall on the flatter portions of burned slopes and in ephemeral channels. Overland flow the following winter scours most of its sediment load from these erodible deposits. The scenario may be repeated several winters after the fire as the rills formed during each runoff period are refilled by dry ravel between storms and during summers.

### Landslides

Landslides were not considered as an important erosional process in the chaparral until the past decade when they were recognized as both an important erosional mechanism (Bailey and Rice 1969) and as a serious threat to life and property (Campbell 1975). They were probably ignored in earlier years because of their infrequency. Campbell (1975) placed the return period of the average landslide-producing storm in the Santa Monica Mountains at between 10 and 25 years. The return period seems to be less than 10 years for the front-country portions of the San Gabriel and San Bernardino Mountains. After being alerted to the significance of landslides by the storms of 1966 and 1969, I found records of soil slips (as they were called) on the San Dimas Experimental Forest in 1933, 1938, 1943, and 1965. These landslides occurred during storms producing about 500 mm of precipitation in a 5-day period, with 150 to 200 mm falling in 24 hours late in the storm. Campbell (1975) suggests that about 250 mm of antecedent precipitation followed by a period of rainfall in excess of 6 mm/hour constitute the conditions necessary for soil slips and debris flows in the Santa Monica Mountains. Bailey (1967) belives that the 12-day (before the end of the landslide-producing storm) precipitation amount is a good descriptor of the landslide-producing capabilities of a storm.

Data from 1966 and 1969 storms on the San Dimas Experimental Forest (Rice et al. 1969, Rice and Foggin 1971) give some appreciation for the effect of storm size on landslide erosion in the chaparral. These data may be affected, however, by the fact that the area burned in 1960. By Bailey's (1967) criterion, the 1966 and 1969 storms have return periods of about 11 and 43 years, respectively. Based on the 24-hour amount, the return periods would be 7 and 22 years. In the 1966 storm, 1.7 percent of the area produced landslides; in 1969, landslides were found on 5.5 percent of the area. In 1966, the erosion rate was 21.1 $m^3$/ha; in 1969, it was 298 $m^3$/ha. In 1966, the gentlest slope upon which a landslide was found was 40 degrees. In 1969, the threshold had lowered to 31 degrees. Campbell (1975) identified a range of 26 degrees to 45 degrees as the most common slope for the occurrence of soil slips. Slips on the San Dimas Experimental Forest were measured on slopes ranging from 31 to 48 degrees.

### Channel Processes

Stream channels constituted a buffer in the routing of sediment from chaparral drainage basins. Virtually all dry-ravel deposits stop there (fig. 2). They serve as magazines of sediment which insure that most high flows occurring will transport sediment from the drainage basin at near their capacity. A good proportion of the landslide deposits will also come to rest in the stream channel because much of the material they transport is not readily carried by the stream. Consequently, sediment tends to accumulate in the stream channel and is flushed out infrequently by high flows, often in the first

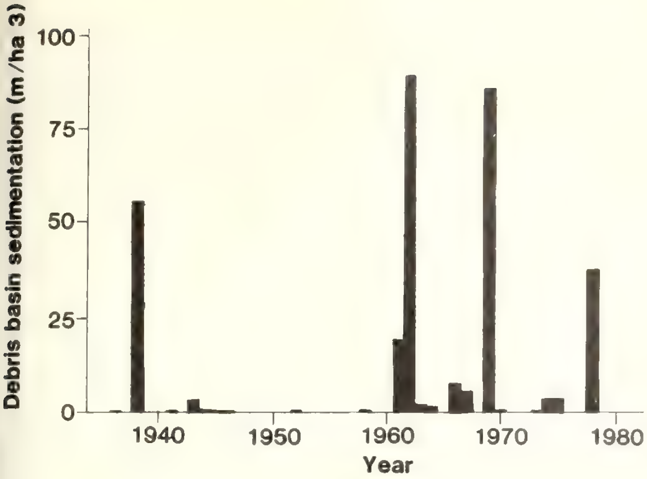

Figure 3.--Annual accumulate in Bell IV debris basin. (Hydrologic Year 1961 and 1962 record combined, sediment distributed between them based on records from nearby basins. Hydrologic Year 1978 is occular estimate, survey data not yet available.)

postfire years. Observed postfire erosion rates depend on the particular sequence of fire and winter rains. For example, in the Bell IV drainage basin on the San Dimas Experimental Forest, about 108 $m^3$/ha of sediment were discharged in the first 2 postfire years (fig. 3). The first year was very dry and the second had normal rainfall. In contrast, nearby Harrow Canyon--which burned in 1968--produced 438 $m^3$/ha of sediment as the result of a storm having a return period of about 35 years occurring the following winter. These interactions between fires and storms tend to cause erratic sediment delivery. Ninety-two percent of the sediment yielded by Bell IV during its 41-year record occurred in 5 years (fig. 3). The dependence on high flows for sediment transport makes fire and soil-water repellency important in chaparral drainage basins.

### Sources of Sediment

Identifying the sources of sediment in the chaparral drainage basins is often difficult. During large storms, when most of the sediment is produced, events that take place late in the storm tend to obscure evidences of earlier erosion. The sources of sediment from Harrow Canyon durng the 1969 flood are an exception. As part of a study after the 1968 burn in Harrow Canyon and Englewild Canyon (Rice and Osborne 1970), I had extensively reconnoitered all of the canyons in the vicinity a few weeks after they had burned. Most of the channels were deeply filled with old alluvial and colluvial sediments. Channel-stabilizing check dams had been constructed on these deposits in some of the canyons. In Englewild Canyon, the pipeline of a private water development ran 600 m up one of the main forks lying on the bank of the creek. After the flood, practically all the channels were scoured to bedrock, the check dams had vanished, and remnants of the pipeline were found, in places, nearly 5 m above the new stream channel. Identifying sediment sources after the flood would have been difficult had it not been for the early reconnaissance and measurements of other erosional mechanisms (column 1, table 1).

Table 1--Sources of postfire sediment

| Erosional processes | Harrow Canyon 1969[1] |  | Estimated typical pattern |
|---|---|---|---|
|  | Observed erosion | Adjusted erosion |  |
|  | Percent |  |  |
| Wind | [2]1 | 1 | 1 |
| Dry ravel | [3]1 | 20 | 40 |
| Landslides | [4]2 | 2 | 1 |
| Surface erosion | [3]22 | 27 | 18 |
| Channel scour | [5]74 | 50 | 40 |

[1] Measurements and estimates cover the period from the fire (8/23/68) until the end of the rainy season (5/9/69).

[2] Estimate .3 mm (based on deposits collected in Glendora).

[3] Measured by 10 erosion plots (each .004 ha, Rice and Osborne 1970).

[4] Mapped from a helicopter and converted to volume using equation in Rice et al. (1969).

[5] Residual obtained by subtracting above estimates from the 438 $m^3$/ha measured in debris basin.

The Harrow Canyon measurements, however, probably underestimated dry ravel because most of it would have occurred before the installation of the plots. Surface erosion is also probably underestimated because of the length of the plots (14.4 m). Allowing for these assumed errors, half of the sediment produced in 1969 came from channel deposits (column 2, table 1). Prefire conditions in Harrow Canyon were unusual. Climatic and vegetative evidence indicated that the winters after the previous fire (more than 70 years earlier) were mild, permitting vegetation to become established on postfire alluvial and colluvial deposits. This vegetation was robust enough to stabilize the channel during the large floods of 1938 and 1943 when many southern-California channels were cleaned out. Apparently, Harrow Canyon channels were scoured in 1969 only because an exceptionally large flood occurred on a freshly burned drainage basin. More typically, erosion after a fire would come about 40 percent from the channel and an equal amount from dry ravel (column 3, table 1).

The previous discussion related to immediate origin of sediment in postfire runoff, not the original source of the sediment. Data on the relative magnitude of various sources of erosion on hillslopes is virtually nonexistent. I believe that about 80 percent of the sediment leaving chaparral drainage basins is initially eroded by gravitational processes of dry ravel and landslides. Channel scour of bedrock (as contrasted to remobilization of deposits) is a minor source of new sediment.

## THE STOCHASTIC PROPERTIES OF SEDIMENT TRANSPORT IN CHAPARRAL DRAINAGE BASINS

### Fire Occurrence

Wind and humidity are importance determinants of fire occurrence. Humidity determines whether ignition takes place, and wind is the primary meteorological control of the rate of spread and ultimate size of the fire.

Topography plays a role in determining the ultimate consequences of a fire. Fires starting low on the slopes usually have a better chance of spreading and inflicting drainage basin damage than those starting on ridges.

Another determinant of effects of fire is the condition of the vegetation (Rothermal and Philpot 1973). The age of vegetation affects both the fuel loading and the proportion of the stand that is dead. Age also affects seasonal changes in green-fuel moisture. These factors, in turn, interact with wind velocities to change the rate of spread. As the result of the interaction of these functions in a manner that is partially random, partially deterministic, a source of ignition may result in nothing--or in a conflagration. The chance of a conflagration increases markedly about 20 years after a fire because of accumulation of enough fuel to carry fire readily (Rothermal and Philpot 1973).

### The Impact of Fire

What a fire does to the soil and vegetation depends both on the characteristics of the fire and the conditions of the vegetation and soil. Impact on soil centers mainly on whether or not a water-repellent layer is created. The degree of water repellency is determined by the temperature and duration of the fire and by the texture and water content of the surface soil (DeBano et al. 1970). A coarse-textured soil with a low moistur content which is subject to a hot (700°C) surface temperature for a relativey short period (10 to 15 minutes) is most likely to develop severe water repellency. The effect of a fire on vegetation depends on its age and vigor (older or weaker plants are less able to regenerate after fire). Less seed survives fires in older stands which tend to burn hotter than younger stands. Plant vigor depends both on the general health an the physiologial stress to which the plant is subject before the fire. Because of opposing seasonal trends of burning condition and plant vigor, the likelihood of a fire is positively correlated with the likelihood of damaging the chaparral and creating soil-water repellency.

The responses of several front-country drainage basins to the storms of 1969 indicate the magnitude of the effects of fire. Average peak discharge from 11 burned drainage basins was sever times greater than the average peak discharge from four drainage basins which had not burned for 9 years or more. Sediment yield from five unburned drainage basins increased by a factor of 14 and for two burned drainage basins by a factor of 120.

### Storms

A storm, whatever its intensity, interacts with drainage basin vulnerability. Vulnerability of a drainage basin to excessive erosion and sedimentation is determined by its soil-water status, density of its vegetation and litter, the degree of soil-water repellancy, and recent storm history. The same storm can have quite a different effect on different drainage basins. For example, during the 1969 storm, a drainage basin that had not burned for 50 years produced landslide erosion at a rate of 16 $m^3$/ha. A similar drainage basin burned the previous summer produced 10 $m^3$/ha, and one burned 9 years before produced 298 $m^3$/ha. In the first drainage basin, good infiltration, and perhaps some decadence in the vegetation, may have led to reduced slope strength. The root system of the former vegetation in the freshly burned drainage basin had not decayed significantly, and the water-repellent layer created by the fire minimized percolation of water to potential failure surfaces. Most of the slides were associated with stream channels and probably triggered by undercutting. Although storm variability might account for the differences in landsliding in these two drainage basins, it is unlikely to be the explanation for the high erosion in the 9-year-old drainage basin. More likely, enough time had elapsed since its fire that infiltration had been restored sufficiently to allow saturation above potential failure surfaces. The regrowing vegetation, however, was not large enough for its root system to restore slope strength. It also could not transpire at a rate that depleted soil water to the same extent as mature chaparral.

### Hyperscedasticity

I would like to propose the term "hyperscedasticity" to describe the sedimentation regime of chaparral drainage basins. It is a regime in which a sensitive terrane reacts to highly variable disturbances producing erratic outputs of sediment. The climate is highly variable, with extremes of rainfall and drought. Many slopes are steep and composed of deeply weathered parent material. Consequently, they are very sensitive to disturbances. Fire is a largely random component playing a prominent role in the environment. So prominent, in fact, that definition of the hydrologic and sedimentologic processes of chaparral drainage basins hinges on an understanding of the role of fire. In addition to the major random components, many minor ones are related to fire behavior, fire effects, vegetative recovery, seismic activity, and channel stability. The sediment regime is further complicated by the existence of thresholds in many important processes, most notably fire and mass wasting. The conditional and independent probabilities associated with these processes and their linkages have resulted in a sediment regime dominated by a few very large events, many insignificant ones, and low predictability.

## MODELING, SEDIMENT BUDGETS, AND SEDIMENT ROUTING

### Process Models

Process models, to even a greater extent than statistical models, are creatures of the computer age. As computers became larger and more economical to use, approximating erosional processes in the memory of a machine became possible. A three-dimensional array could describe the physiography of the drainage basin to whatever detail was deemed necessary. Based on physical laws or empiric data, rules could be incorporated governing how water or sediment moved from node to node within the array. Such models have proved useful, especially in well-behaved cases. They have the intuitive appeal of being similar in form to the prototype system.

Just how strong is the similarity between actual conditions and process modeling of erosion and sedimentation? From a practical point of view, processes must be approximated by lumping various components in time, space, and function. After these comparisons are made, the model is then usually "tuned" until it will reproduce a set of empiric data. Such a procedure invalidates the claim of generality. Proponents argue that process models are extrapolatable to different areas because they are based on physical relationships, and physics does not change with time and distance. This claim of robustness has been compromised by the approximations and by incorporating calibration procedures into process-model building.

The calibration of process models carries another risk. Because their data requirements are exacting, the available suitable data sets tend to be small. When a small sample is drawn from a time series that produces significant effects only infrequently, the sample is likely not to include such an event. This attribute of the calibration of process models tends to cause underestimation of the variance of the dependent variable, which is particularly undesirable because accurate reproduction of large events is critical to model utility. If, on the other hand, the sample happens to include a large event, the large variance computed may be misinterpreted as "typical."

### Empiric Models

Multiple regression is the principal empiric model used. Certainly, it has the longest history as a predictive tool in hydrology and sedimentation. This discussion will, in the main, be relevant to other statistical procedures as well. When using such models, the hydrologist breathes a prayer: "Dear Lord, let the world be linear and Gaussian." He desires linearity so that the structural form of the analysis is correct and normality so that he can estimate the precision of coefficients. The prayer is rarely answered. Nonetheless, empiricists are forced to jam the world into the regression straightjacket and hope that--even if their prayer is not answered--the central-limit theorem will come to their rescue. To make that rescue more likely, they are tempted to include more and more observations of poorer and poorer quality in their analyses so that $\underline{n}$ may more closely approach infinity. Most modern computer utilities offer programs that assist the analyst in selecting an optimum set of independent variables. But, no resort to "heroic statistics ... offers a real substitute for solid data" (Philip 1975).

Assuming that the previously mentioned problems have been more or less satisfactorily resolved, the empiricist still has only what could be charitably termed a pseudophysical model. His partial-regression coefficients express the relation between each independent and the dependent variable. The "independent" variables, however, are rarely independent. Some are correlated (perhaps an artifact of the data base), and others have functional relationships (such as soil with slope, aspect, and elevation). This means that the regression coefficients are only hinting at a functional relationship. To their credit, regression analyses facilitate the consideration of a much larger set of casual variables than would be practical for most process models. They also may have a slight advantage over process models in that if extreme events are included in the data set, the least-squares analysis will tend to cause them to dominate the form of the resulting regression equation. They share the same sampling problems that cause process models to be unlikely to include important events, however.

## Monte Carlo Models

Models based on Monte Carlo simulation may incorporate desirable features of both process models and empiric models. Similar to process models, a Monte Carlo model would form a chain of conditions or processes that feed one another. The chain would begin with meteorological inputs and terminate with the delivery of sediment. Unlike in a process model, the nodes in the model would not have a spatial relation to one another and would not form a grid in two or three dimensions. Rather, the nodes would define a series of relations linking inputs to the output of sediment. Both the mean and variance of a function would be defined at most nodes. In this fashion, both the estimate of the presumed relation and the uncertainty associated with that estimate enter into the simulation. Although conceiving these nodes as bivariate relations is easiest, no inherent reason prevents nodes representing multivariate relations.

Each time the flow of the program reaches one of the nodes, it branches to a subroutine that generates random numbers. The number so acquired is then applied to the probability distribution of that function to determine the value of the function to be used in that simulation. The uncertainty related to various functional relationships is thus retained explicitly in a model, which is otherwise deterministic. The model could be cycled many times in the analysis of any particular set of circumstances so as to yield a spectrum of possible outputs. The analyst would have an estimate both of the expected response to a particular situation and of the probability of very beneficial or very disastrous consequences. Management decisions might hinge more on the extreme outcomes than upon the expected outcomes.

A much-simplified case will be used to give a little further appreciation for the functioning of a Monte Carlo model. It treats mass wasting as a function of storm size and fire history. Sedimentation is handled by a delivery ratio, and none of the interactions among sediment processes is considered. The greatest simplification, however, is in treating the process as an annual series rather than considering within-year temporal variation in many of the functions.

In the example, the objective is to estimate mean long-term production of sediment from mass movements. A further assumption is that the functions shown in figure 4 have a sound basis in theory and also in empiric data. The first step in the simulation is to estimate the size of the largest storm of the season by sampling from the probability distribution of maximum annual storm precipitation (fig. 4a). If the storm size obtained from the samping is less than some critical value (x), the remainder of the simulation is irrelevant and can be bypassed because the storm is so small that the probability of landslides is essentially zero regardless of vegetative condition. In this case, the occurrence of the trial would be recorded and a new drawing made from the storm size distribution.

If the drawing from the storm size distribution results in the storm larger than the threshold size, the remainder of the simulation comes into play. The next random drawing is from the population distribution of possible ages of chaparral (fig. 4b). Vegetation age--more correctly, its size and vigor--largely determines drainage-basin response to the storm.

The age is related to resistance to landslides in figure 4c. Resistance is highest immediately after a fire because the root system is still intact and reduced infiltration is likely because of water repellency. Resistance declines in the next few years as infiltration is restored and root decay sets in. Then, after about 8 years, the slope becomes more resistant as roots develop on sprouting plants and new seedlings. Between 25 and 30 years, a slight decline takes place as the pioneer species such as *Ceanothus* are crowded out by more long-lived species. The decline soon levels out as the stand enters senescence, with a gradual turnover of plants as individuals die and are replaced. The curve in figure 4c is patterned after root biomass of redwood (*Sequoia sempervirens* (D. Don) Endl.) in northwestern California (Ziemer, R. R., 1700 Bayview Drive, Arcata, California, personal communication). It is also similar to curves developed for the uprooting resistance of trees in Japan (Kitamura and Namba 1966). I have assumed that the variance of this trend in landslide resistance would increase markedly after a fire and then decline. The basis of that assumption is that, in the early years, recovery would be dependent on postfire weather, the age of vegetation at the time of the previous burn, and the severity of the previous burn. As the stand gets older, it comes to express the ecological potential of the site, regardless of the point at which it began its recovery. Consequently, the variance in very old stands becomes rather small.

From the resistance obtained from the relationship of figure 4c, the expected volume of erosion from an average landslide-producing storm is computed using a function relating landslide volume to resistance (fig. 4d). This mean response is then increased or decreased according to storm size, using the relationships in figure 4e. In this case, the variance results from the fact that storms that are nominally identical, in terms of figure 4a, actually have different capacity to produce landslides because of the distribution of rainfall intensity within the storm. Between-storm variability in erosion is assumed to decline for larger storms.

The last step in this model is to estimate sedimentation using a delivery ratio (fig. 4f). The mean response assumes debris resulting from the landslides during small storms will have low fluidity and, consequently, low delivery ratios. As the debris increases, the delivery ratio increases to a maximum and then declines as landslide debris becomes so prevalent that it greatly exceeds the ability of the stream to carry it from the drainage basin. The variance responds to those same factors. In small storms, the delivery ratio depends on the location of slides throughout the drainage basin and is, therefore, highly variable. As storm size increases, delivery to the stream increases and the variance declines. With large amounts of debris, the system becomes stream-power dependent and the variance is correspondingly reduced.

The model could be run for a specified number of cycles or halted when estimates of the mean and variance of sediment production had stabilized. In addition to generating information about the distribution of possible sediment outputs, a Monte Carlo model could yield data concerning the stochastic properties of the time series of sediment outputs. These possibilities make the application of Monte Carlo simulations to sediment outputs worthy of investigation. Bear in mind, however, that although sampling from probabililty distributions is frequent in the use of Monte Carlo models, the accuracy and precision of the estimates of sediment production are unknown. Even if all the variates used in their development were normally distributed, no general or exact way exists for computing the parameters of the output distribution based on the estimates of the various inputs. Usually a Monte Carlo model will rest on a more uncertain foundation. Some functions will be well defined by empiric data (figs. 4a, 4b), others will be built of sketchy information and extrapolation (fig. 4c), and still others will reflect only theory or hypothesis (figs. 4d, 4e, 4f). Therefore, in spite of the intuitive appeal of Monte Carlo models, their results have to be accepted on faith or calibrated with empiric data.

Some statistical problems are relevant to all types of models: process, empiric, or Monte Carlo. Paramount among them is the hyperscedastic

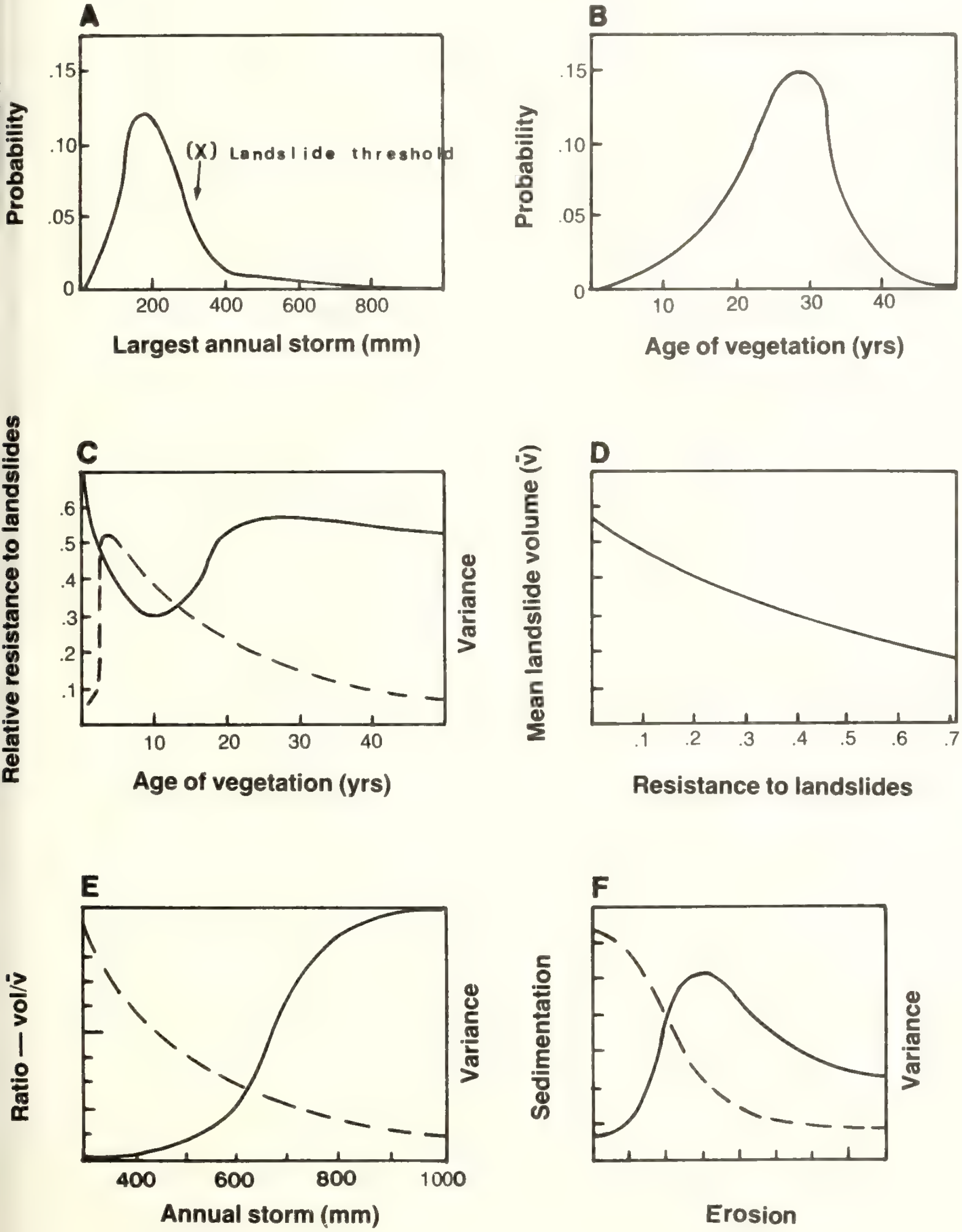

Figure 4.--Functions (solid lines) and their variances (broken lines) used to sketch the structure of a simulation of landslide erosion in Chamise chaparral.

nature of most of the phenomena, especially the outputs. This has the effect of making the relevant data base extremely small. The information from the Bell IV drainage basin probably represents something like 4.5 "years" of record for use in building a sedimentation model--even though it took 41 years to collect. This small, relevant data base places a heavy burden on modelers; they have been able to observe very few of the possible interactions of a complex process.

Because of the hyperscedasticity of the phenomena and the way data are collected, the robustness of the coefficients should be doubted: To what extent do they estimate their parametric values, and to what extent are they the result of spurious correlations in the developmental data? And what about the developmental data; are they from a stationary time series? Are current estimates of parameters (even if accurate) valid estimates of their future values? Models are often constructed because changes are planned for a drainage basin. Normally, we had no a priori way of knowing how well models will hold up under changed conditions. Are the processes defined in sufficient detail? These questions, too, will have to be resolved on faith. Each model builder must wield Occam's razor, attempting to include all the complexity necessary for accurate prediction, but nothing more.

The small, relevant data base for modeling hyperscedastic processes presents a paradox: Good models require a large amount of good data for their development, but the lack of a long and abundant data stream is just what makes necessary the development of models of erosion, sediment transport, and other hydrologic phenomena. Clearly we are in a "trans-scientific" environment. Weinburg (1972) has introduced this adjective "trans-scientific" to describe "questions which can be asked of science and yet cannot be answered by science." Although posing such questions as rigorously testable hypotheses is possible, conducting the research necessary to answer them is impractical (if not impossible). In response to this dilemma, "It remains our obligation to insure that our methods are as scientific and objective as possible. Let us at least work towards a situation where the trans-scientific judgements which practical hydrologists are forced to make are informed and sustained by a truly scientific hydrology: a skeptical science with a coherent intellectual content firmly based on real phenomena (Philip 1975)."

Process models, because of their data requirements, will ususally have applicability only to the management of drainage basins where high values are at stake--values which can justify the expenditure of the resources required for their use. In most circumstances, to quote from Philip (1975), "The task of performing an accurate detailed physical characterization and using this in a reliable predictive calculation is scientifically feasible; but would almost always demand for its proper performance, the expenditure of resources out of all proportion to the benefits." Empiric models are at the other extreme. Although requiring only a modest expenditure of resources, their rigid structure dictates that they lack a firm basis in real phenomena.

Monte Carlo models may offer a feasible solution to some trans-scientific hydrologic problems. Their resource requirements are intermediate between process models and empiric models. Like empiric models, they consider random variation explicitly. In common with processed models, they permit an amalgam of empiric information, theory, and (if necessary) conjecture. Hopefully, the result can satisfy Philip's (1975) desire for "a coherent intellectual content firmly based on real phenomenon."

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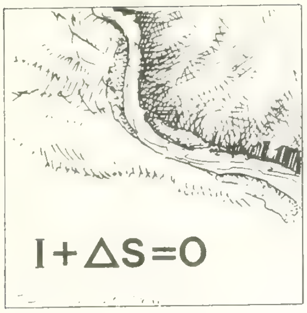

# Use of a Physical Model to Determine Effects of Periodic Erosion in Steep Terrain on Sediment Characteristics and Loads

Michael D. Harvey

## ABSTRACT

A "similarity-of-process" (Hooke 1968) model was constructed in the Rainfall Erosion Facility (R.E.F.) at Colorado State University, Ft. Collins, Colorado. Mass slope failure and the character of resulting sediments were investigated. Total sediment yields immediately after slope failure were dominated by the suspended load. Through time, sediment yields diminished but then increased again and were dominated by bed-material load. Total sediment loads were subdivided into the components of traction, saltation, and suspension load using the methods proposed by Visher (1969) and Middleton (1976). During a single storm event in which water discharge varied from 0.3 to 2.8 liter/second, sediment discharge varied by an order of magnitude and exhibited hysteresis. Suspended loads peaked on the rising limb, and traction loads peaked on the falling limb of the hydrograph. Sediment discharge behavior observed in the R.E.F. is compared to behavior demonstrated by data collected in the field in both New Zealand and Colorado.

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Michael D. Harvey, Graduate Student, Earth Resources Department, Colorado State University, Fort Collins, Colorado 80521.

## NTRODUCTION

ardware modeling in geomorphology may be defined s the study, under closely monitored or controled experimental conditions, of a physical epresentation of a selected geomorphic feature Mosley and Zimpfer 1978). Hooke (1968) conidered that a model could be treated as a small rototype in its own right--not representing a pecific location, but rather the general features f many locations. He referred to this approach s "similarity of process." He considered that ross scaling relations must be met, the model must reproduce some morphologic characteristic of he prototype, and the processes producing this characteristic in the model must have the same effect in the prototype. Using this approach, the generally recognized disadvantages of physical models--scaling ratios, initial conditions, and boundary conditions--can be countered. Physical modeling, although used predictively and descriptively, is inherently incapable of providing the last link in the chain of scientific investigation--the theory or law--because the results can only be qualitatively and cautiously applied to the real world (Mosley and Zimpfer 1978). The advantages and disadvantages of hardware modeling in geomorphology have been summarized by Mosley and Zimpfer (1978). The use of models can be justified in the generation and testing of hypotheses that can then be investigated in the field.

The interactions between slopes and channels as a result of low-frequency, high-magnitude catastrophic events are difficult to measure in the field. An experiment was therefore conducted in the R.E.F. to test the following hypotheses: After mass slope failure, sediment yield from a drainage basin is dominated initially by suspended load; through time, sediment yield is dominated by bed-material load; the coarser fractions move downstream in waves or pulses; and the changing character of the sediments results in changes in downstream channel morphology. This paper presents the results of sedimentologic investigations of these hypotheses and reviews some of the pertinent literature.

Adams (1978) reported on the effects of the Inangahua earthquake of 1967, which delivered $52 \times 10^6$ $m^3$ of material to the Buller River on the west coast of the South Island of New Zealand; he considered that 95 percent of the debris introduced to the channel was transformed rapidly into suspended load, and the remaining 5 percent remained in the channel and was transported as bedload. Pain and Bowler (1973) concluded that about half of the $27 \times 10^6$ $m^3$ of sediment delivered to the channel as a result of the Madang earthquake in New Guinea reached the sea in 6 months. Both authors consider that suspended loads were double those of the preslope failure period. On the other hand, Hayward (1978), reporting on the Torlesse Stream in the South Island of New Zealand, concluded that, during 1974-77, suspended sediments contributed less than 10 percent of the total annual yield of sediment and that the bulk of the sediment transported is moved as bedload derived from in-channel storage and bank failures. The stored sediments represent the coarser fractions of the debris introduced to the channel system by catastrophic slope failures as the result of a severe thunderstorm in 1957. The work cited probably encompasses the variations in proportion of suspended load to bedload through time after catastrophic slope failures.

## EXPERIMENTAL METHODS

Using Hooke's (1968) similarity-of-process approach, a drainage basin of 5 x 10 m dimensions was constructed in the R.E.F. The basin was connected by a hydraulically efficient conduit (Z) to a 12 x 2.2 m straight channel (main), which was intended to simulate a downstream, nonheadwaters channel reach (fig. 1). The morphometric characteristics of the drainage basin and main channel are summarized in table 1. During the construction of the divides, a subsurface layer was compacted to provide a failure surface to facilitate mass movements of the slope materials. The material used in slope construction was moderately cohesive and ranged in size from -3 to 5 (Folk 1965); the material was considered by Mosley (1975) to allow accurate reproduction of most aspects of natural river morphology. The grain-size distribution curve for "parent material" is shown in figure 2. Using Shields' (1936) approach, the channels were determined to be able to transport all sediment size classes in the basin. Precipitation was only applied to the drainage basin from a set of overhead sprinklers. Rates could be varied as required, and distribution over the basin was reasonably uniform.

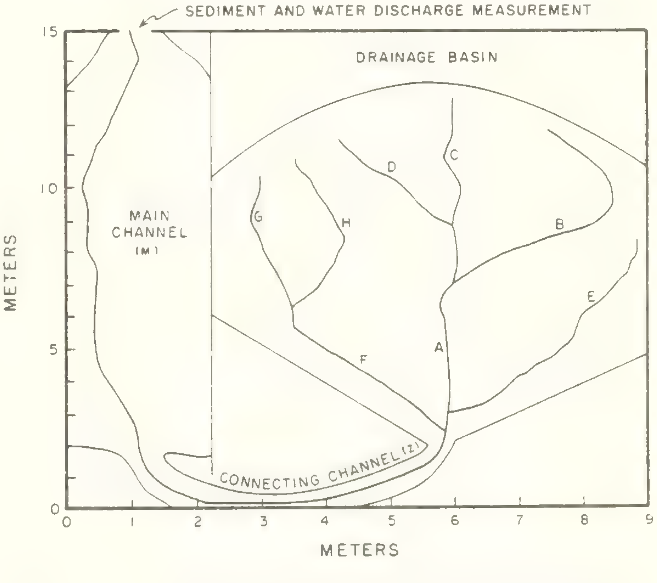


Figure 1.--Plan view of R.E.F. showing drainage basin, connecting channel (Z), main channel (M), and measuring point.

At the end of the main channel, total discharge of water and sediment was measured at closely spaced intervals during the course of each run, which was intended to simulate a storm event. Initially, low-intensity precipitation was applied to the drainage basin to simulate low-flow conditions. A 5-minute burst of high-intensity precipitation was then applied to the drainage basin to simulate a

Table 1--Morphometry of R.E.F. model

| Drainage basin or channel | Initial channel slope | Valley slope ranges | Area | Basin shape | Relief ratio | Drainage density | Ruggedness |
|---|---|---|---|---|---|---|---|
| | | Degrees | Square meters | | | | |
| Entire drainage basin | -- | 22-44 | 51.97 | 0.499 | 0.066 | 0.699 | 0.461 |
| A | 0.0858 | 21-43 | 27.63 | 0.257 | 0.064 | 0.664 | 0.441 |
| F | 0.0771 | 25-44 | 14.63 | 0.266 | 0.093 | 0.844 | 0.581 |
| E | 0.0769 | 20-44 | 9.84 | 0.271 | 0.084 | 0.574 | 0.290 |
| Main (M) | 0.0045 | -- | -- | -- | -- | -- | -- |
| Connecting (Z) | 0.0038 | -- | -- | -- | -- | -- | -- |

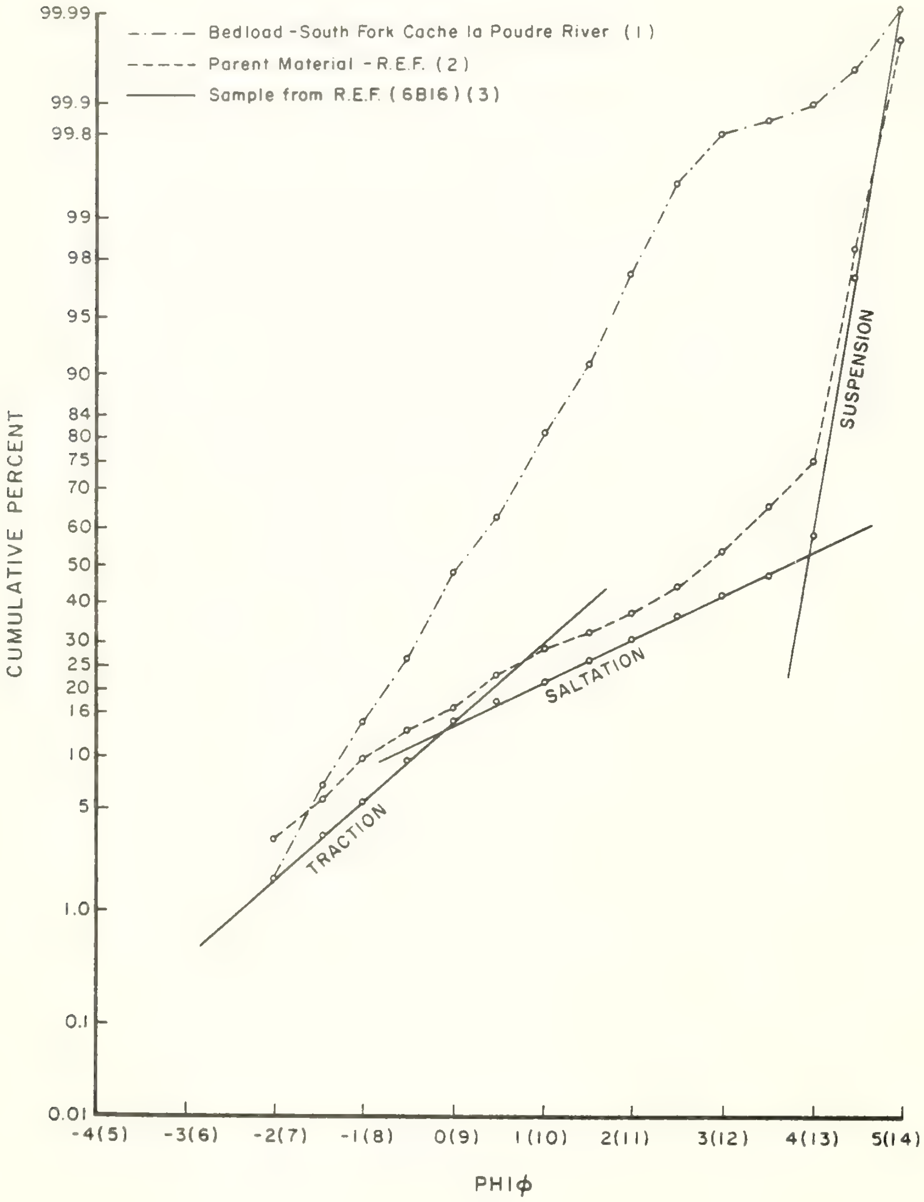


Figure 2.--Log probability plots of: (1) bedload sample from the South Fork of the Cache la Poudre River, Colorado; (2) "parent material" used in R.E.F.; (3) sample 6B16 from the R.E.F.

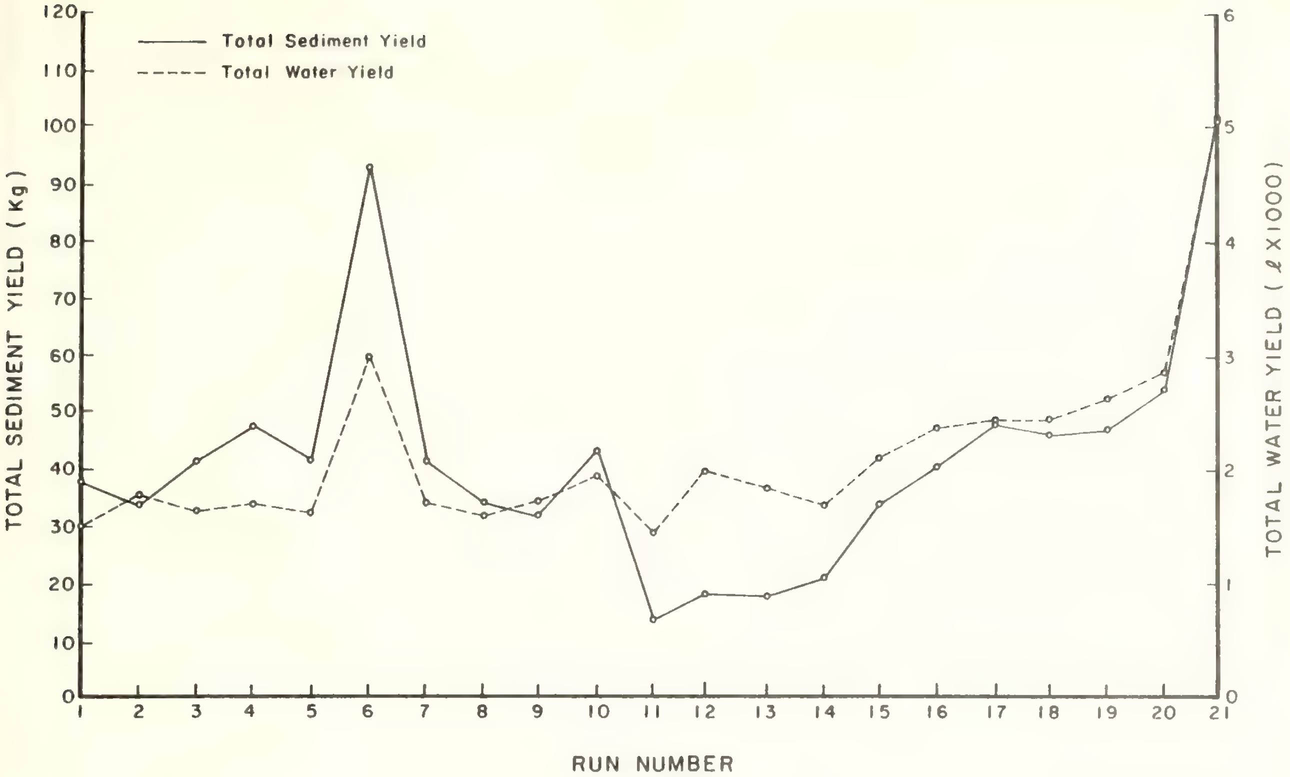


Figure 3.--Total sediment and water yields for 21 runs in the R.E.F.

major storm. After the 5-minute burst, precipitation intensity was again reduced until steady discharge conditions were attained, and the system was then shut down. Sediment samples were ovendried and then sieved according to standard techniques. Grain-size statistics were obtained using the methods determined by Folk (1965).

Sediment was delivered from slopes to channels by three principle means: slope wash, debris slides, and raindrop splash. The debris-slide sites generally developed into gullies with time. Lateral migration of channels caused the undercutting of slopes, which also resulted in slope failures.

To understand the sedimentology of the system, we need to know what fraction of the total sediment yield in each run was transported by the three transport mechanisms of traction, saltation, and suspension. The scale of the operation prevented direct measurement of modes of transport, and therefore the method proposed by Visher (1969) and Middleton (1976) for subdividing the total load into the transport components was investigated. The method was tested using grain-size analyses of bedload collected with a Helley-Smith sampler in the South Fork of the Cache la Poudre River, Colorado. If the method is valid, bedload data should plot as a single straight line on log probability paper. An example of the results is shown in figure 2. Statistical analysis of the bedload data indicated that a single population was being investigated and provided further support for the method. On the basis of the results from the bedload data, I decided to use the method to subdivide the total sediment samples obtained in the R.E.F. Grain-size data from 100 R.E.F. samples were plotted on log probability paper. An example is provided in figure 2.

## RESULTS

Sediment yields (fig. 3) and transport rates for 21 runs in the R.E.F. were calculated. Runs 1 to 3 probably represent the response of the system to the effects of model construction. During Run 6, mass movement failures occurred in the drainage basin. Total sediment yield for the run was 93.5 kg, and suspended sediment (size range of 4 and less) constituted 62.6 percent of the yield. Runs 7 through 11 showed a general decrease in total sediment yield per run (41.7 kg to 13.4 kg), but the yields were still dominated by suspended sediments (58.6 percent to 59.7 percent). The decrease in total sediment yields per run can be attributed to a reduction in supply of sediment from the mass-movement detritus. The suspended sediments were rapidly transported, but the coarser fractions were stored in channels as evidenced by an overall increase in mean bed-elevations of all the headwater channels. Total sediment yields per run increased from Run 12 through Run 19 (18.2 kg to 46.9 kg). The contribution of suspended sediment to total yields fell from 53.5 percent to 43.9 percent. The increase in total sediment yields and the reduction in the proportion of suspended sediment can be attributed to the mobilization of coarser fractions stored in the channel, as demonstrated by the overall reduction in mean bed-elevation of headwater channels and the construction of fans in the main channel. Small mass-movement failures occurred in the drainage basin during Run 20, and this is expressed by an increase in total sediment yield (54.0 kg) but, more importantly, in the proportion of suspended sediment (50.6 percent).

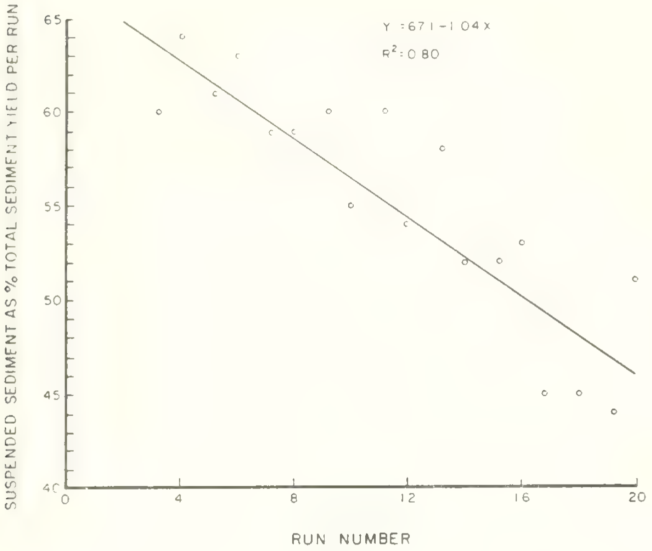
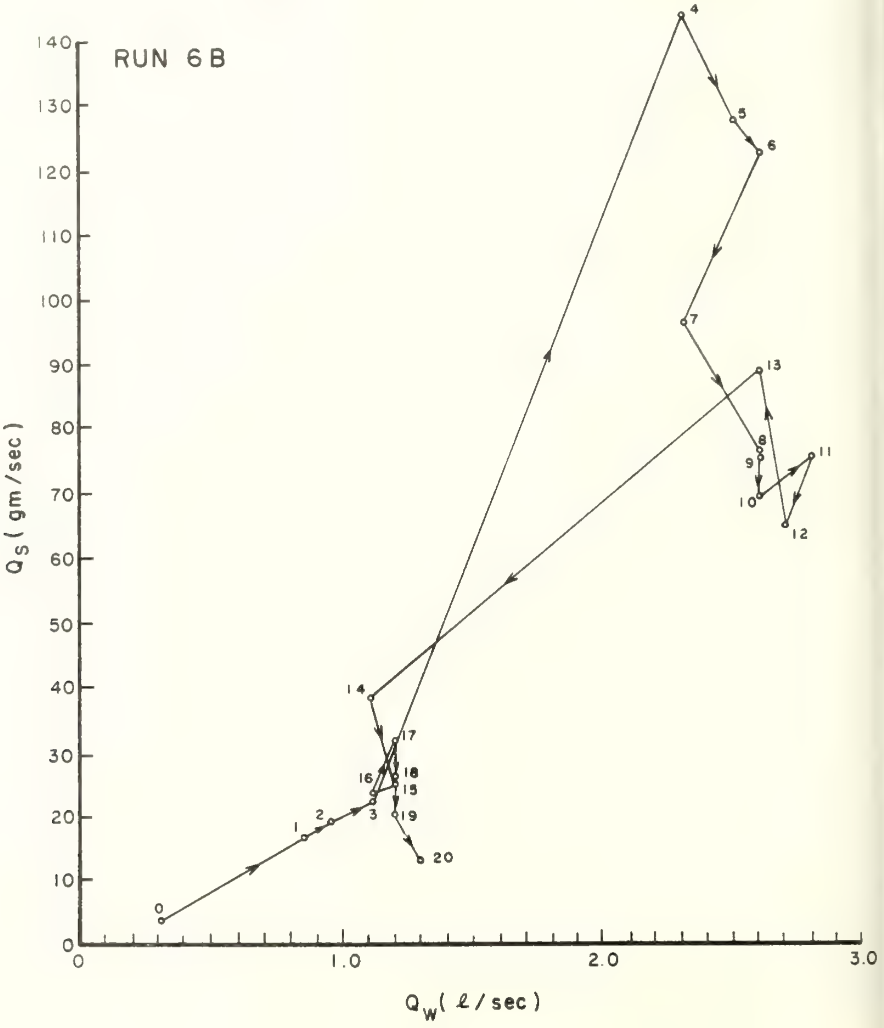


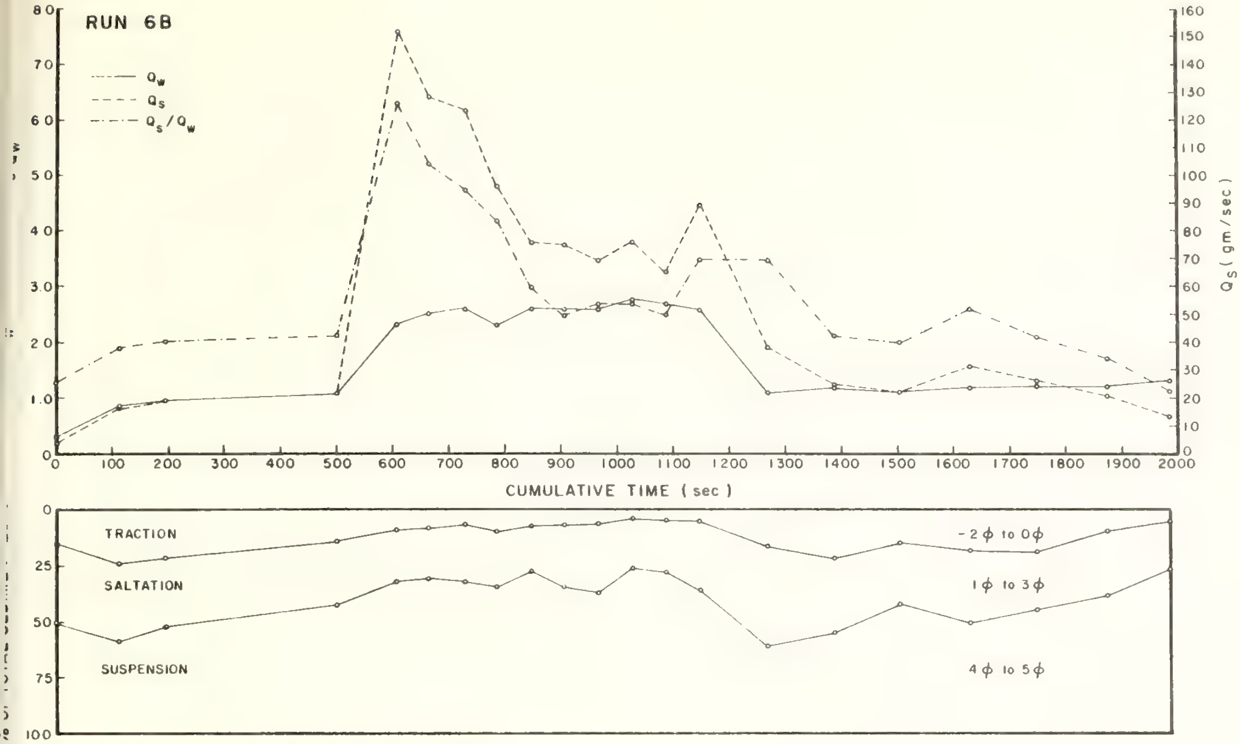
Figure 4.--Suspended sediment as percent of total sediment yield per run versus run number.

Figure 4 shows the relation of the proportion of total sediment yield delivered as suspended sediment (Y) to run number (X), described by the equation: $Y = 67.1 - 1.04X$ $(R^2 = 0.8)($ $= 0.001)$.

Sediment-transport rates ($Q_s$) during the course of individual runs did not increase linearly with water-discharge rates ($Q_w$). Figure 5 summarizes the discharge data for Run 6, which is presented as a general example. The discharge rates are characterized by a series of hysteresis loops. Gregory and Walling (1973) report similar behavior for suspended sediments. Transport rates were from 5 to 20 g/second (points 0-3) at $Q_w$ values up to 1.3 liter/second. As $Q_w$ increased to 2.3 liter/second, $Q_s$ increased to 140 g/second (point 4), and sediment type was dominated by suspended sediment. Transport rates fell to 68 g/second (point 10) while $Q_w$ remained essentially constant. As $Q_w$ increased to a maximum of 2.8 liter/second, $Q_s$ increased to 76 g/second (point 11) and was the result of an increase in the amount of bed-material load being transported. On the waning stage, $Q_s$ increased to 88 g/second (point 13) before falling substantially to 37 g/second (point 14). The increase was from increased transport of the coarsest fractions. Figure 6 presents the changes in grain-size distribution during the course of Run 6.

Figure 5.--Hysteresis loops of total sediment and water discharge for Run 6.





igure 6.--Summary of discharge data and edimentology, Run 6.

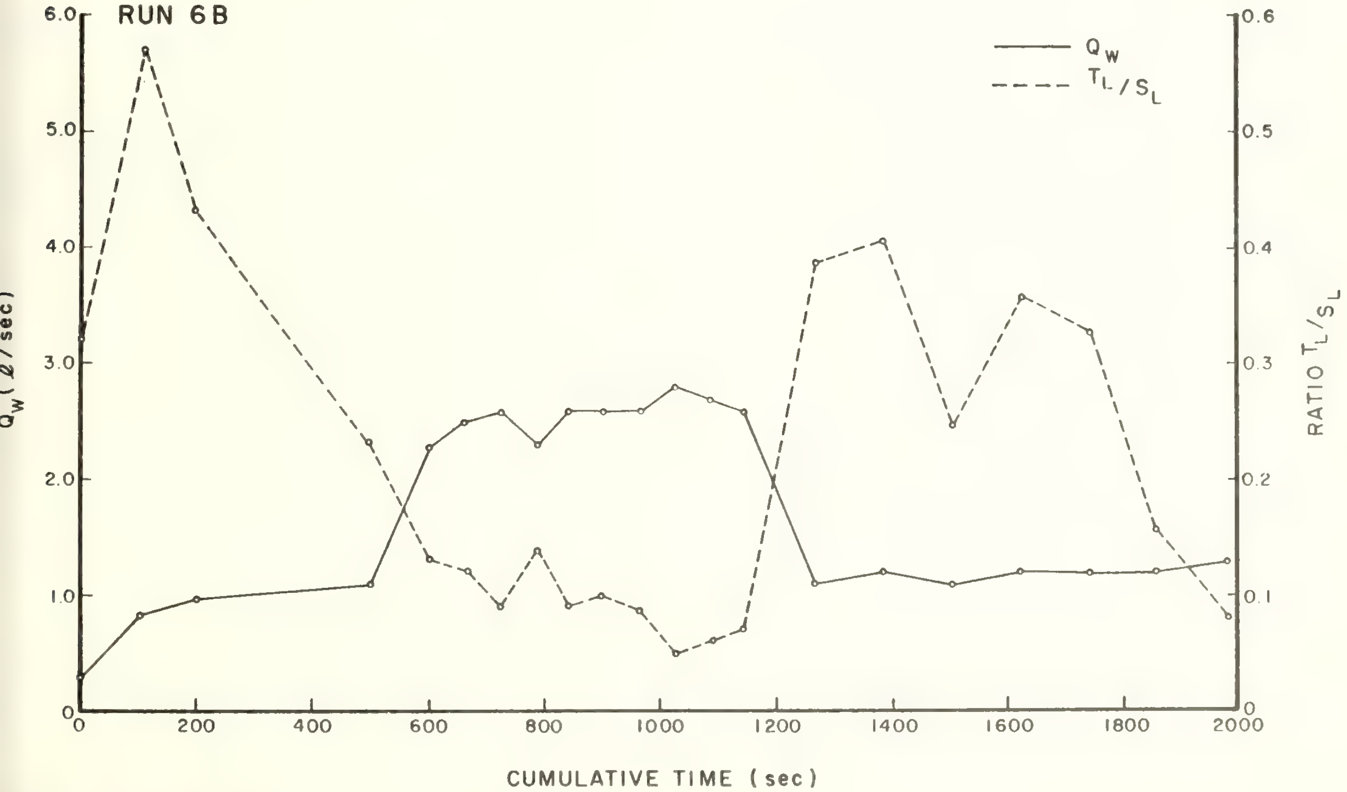


Figure 7.--Water discharge and ratio of traction load to suspended load ($T_L/S_L$) for Run 6.

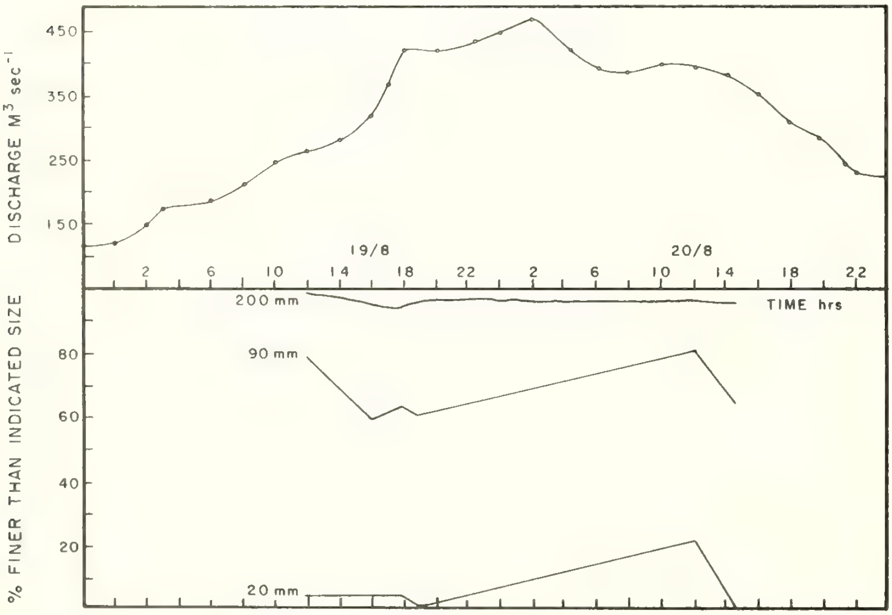
In small drainage basins sculptured by fluvial processes, suspended sediment loads tend to peak before the peak of the hydrograph (Porterfield 1972, O'Loughlin et al. 1978). This phenomenon was observed in the R.E.F. during many runs, but the peaks did coincide in some runs--especially the earlier ones where large volumes of material in the suspended-load size range (4  and less) were available for transport. In contrast to the suspended load, the coarser fractions (-2  to 3 ) peaked after the peak of the hydrograph. W. W. Emmett (personal communication, U.S. Geological Survey, Denver, Colorado) has noted the same phenomenon in the East Fork River in Wyoming.

These phenomena may be attributed to three possible causes. Heidel (1956) established that the peak of sediment concentration progressively lagged behind the flood peak, and this may be what occurred in the R.E.F. Second--at the peak of the discharge--large volumes of sediment are being transported, which can lead to localized aggradation of some channel reaches. Reduction in sediment delivery from the drainage basin on the waning stage of the hydrograph leads to scouring of the locally aggraded reaches, thereby increasing the amount of material available for transport. Third, sediment supply falls off more rapidly than the water discharge. One feature in all runs was that with the low water discharges on the rising stage, a relatively high proportion of coarser material occurred in the sediment samples. This is attributed to continuation of scour of locally aggraded reaches before sufficient sediment is moved out of the drainage basin to prevent it. The relative contributions of traction load and suspended load over the course of Run 6 are presented in figure 7, in which the ratio of traction load to suspended load is plotted with the hydrograph.

Hayward (1978) showed similar trends of early and late coarse material discharge during the course of a storm in the Torlesse Stream, South Island, New Zealand (fig. 8). Bedload data collected in the South Fork of the Cache la Poudre River, Colorado (Doehring and Ethridge 1979) showed similar trends (fig. 9).

## SUMMARY AND CONCLUSIONS

Sediment yields and transport rates resulting from periodic mass movements were measured for 21 runs in the R.E.F. Slope failures first occurred in Run 6 and were reflected in the total sediment yield (93.5 kg), but more importantly in the composition of the total yield (62.2 percent suspended sediment). Total sediment yield per run fell through Run 11 (13.4 kg), but suspended load was still the dominant component of total load. Reduction in total sediment yields was accompanied by increases in mean bed-elevation of all headwater channels where mass movements had occurred. In Runs 12-19, total sediment yields per run again increased (46.9 kg), but bed-material load became the dominant component of total load (56.1 percent). The change in composition of the total yield was accompanied by reduction in mean bed-elevation of headwater channels and the formation of fans in the main channel. During Run 20, small mass movements occurred in the drainage basin and were expressed as an increase in total sediment yield (54.0 kg), but more importantly by an increase in the proportion of suspended sediment (50.6 percent).



HAYWARD (1978) - TORLESSE STREAM (NEW ZEALAND)

Figure 8.--Water discharge and sedimentology for storm event of 19/8 to 20/8 in the Torlesse Stream, New Zealand (after Hayward 1978).

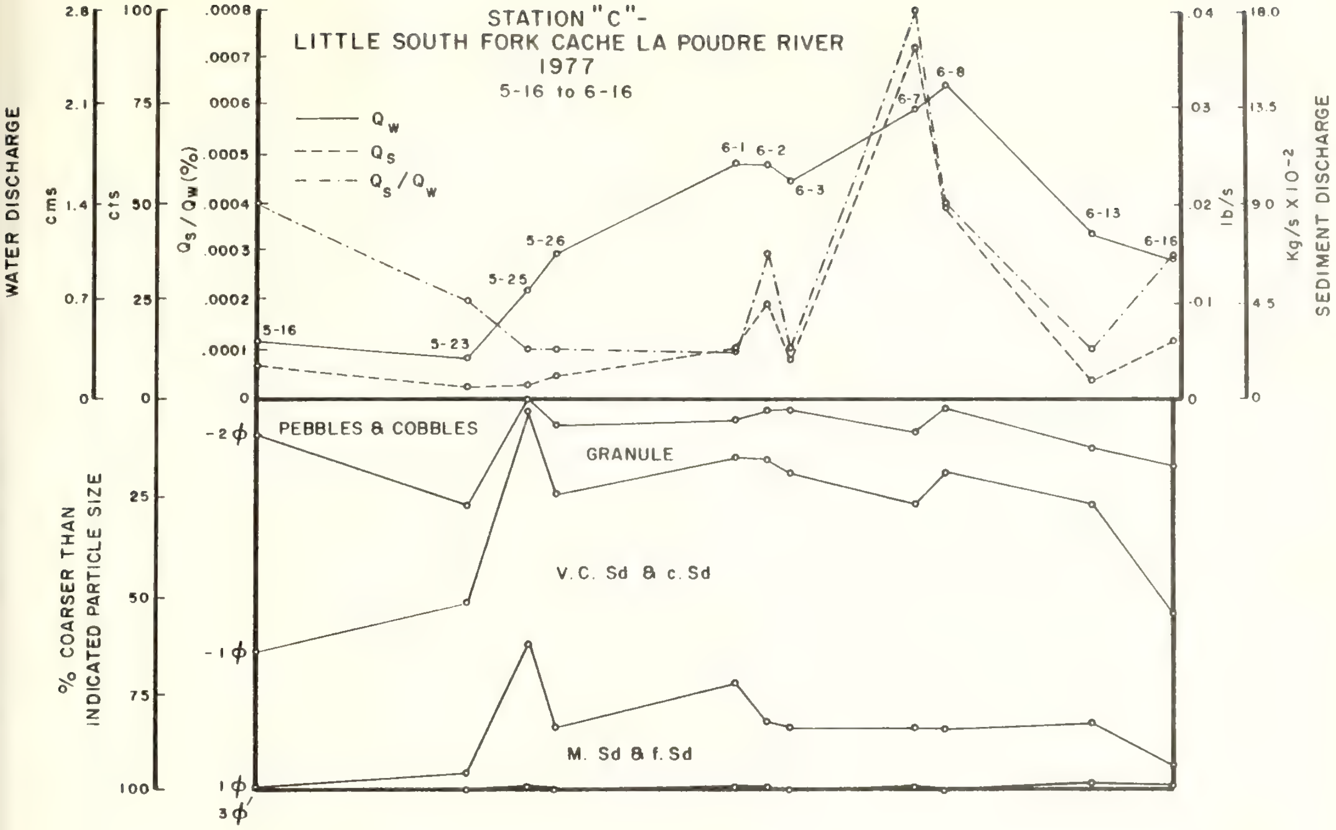


Figure 9.--Water and sediment discharge and sedimentology for 1977 runoff season, South Fork, Cache la Poudre River, Colorado.

The data generated in the R.E.F. agree in general with the results reported by Pain and Bowler (1973), Adams (1978), and Hayward (1978). The data also confirm that the quantities and composition of sediments transported after major slope failures change with time. The decrease in the proportion of suspended load is not as dramatic as would be expected in the field because the unvegetated slopes in the R.E.F. produce high background levels from the impact of raindrops.

Sediment-transport rates during the course of individual runs exhibited hysteresis. The first peak of sediment was dominated by suspended sediments and occurred before the peak of the hydrograph as a result of maximum sediment production or availability in the early stages of the storm event. As the hydrograph peaked, a second sediment peak occurred and was related to an increase in the transport of bed-material load. The third peak of sediment occurred on the waning stage and resulted from increased transport of the coarsest fractions, possibly because of the scour of locally aggraded and oversteepened reaches in the channel. An early increase in the percentage of coarse material at low discharges on the rising limb was observed and is attributed to continuing scour of locally aggraded reaches. Early and late peaks of coarse material were also observed in rivers in New Zealand and Colorado.

Hooke's (1968) similarity-of-process approach to physical modeling in geomorphology has been used in this study. Although model results must be viewed with caution when applied to the field situation, some observations indicate that the R.E.F. is behaving as a natural system, and may be used to indicate areas where field research could be directed. The similarities in the sedimentology of the R.E.F., field data collected in New Zealand and Colorado, and that reported in the literature suggest that sediment yields and composition change through time after major slope failures in headwater zones. Changes in sediment-rating curves with time may reflect this and could possibly be used to predict the downstream movement of waves or slugs of coarse material. S. Schumm (personal communication, Colorado State University, Ft. Collins, Colorado) considers that the destabilization of previously stable river reaches may be the result of this phenomenon. A study of the Niobrara River is currently underway to test this hypothesis.

## ACKNOWLEDGMENTS

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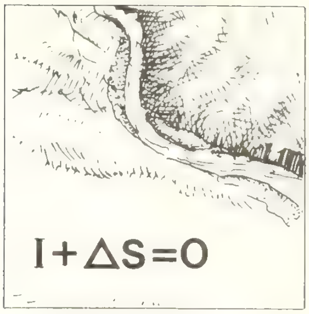

# Episodic Behavior in Badlands: Its Effects on Channel Morphology and Sediment Yields

Frank W. Bergstrom

ABSTRACT

Variable sediment yield and valley and channel morphology in rapidly eroding steepland drainage basins is referred to as episodic behavior. Three zones along channels can be distinguished on the basis of channel and valley morphology. Sediment production is discontinuous as headwater storage elements are periodically depleted and refilled. During a sediment production event, stored bed sediment is eroded from the headwaters and transported downstream, overloading the channel system. The headwater zone (zone 1) is a zone of material flushing. The transition zone (zone 2) braids during flushing of material from zone 1 and trenches during nonflushing periods. the lower, braided zone (zone 3) is a site of deposition as in-channel alluvial fans are locally built and reworked. Morphologic changes among the three zones are out of phase. Maximum sediment storage at a station progresses downstream. The types of sediment-storage elements vary from zone to zone. Drainage-basin sediment yield varies in response to these morphologic changes. Sediment delivery ratios range from less than 1 to 3 during a major sequence of sediment production, deposition, and erosion.

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Frank W. Bergstrom, Geomorphologist, Nerco, 111
S.W. Columbia, Suite 800, Portland, Oregon 97201.

## INTRODUCTION

Erosion and sedimentation in mountain environments have characteristics distinctive from areas of lower relief. Helley and LaMarche (1973) showed that exceptionally large storm events are predominantly responsible for stream valley development in mountain basins. Their investigations in north coastal California indicate that only several of these valley-modifying events have occurred in the last 400 years. These episodic storms produce and transport large quantities of sediment. Such behavior can be expected to produce highly variable sediment yield at the basin outlet.

A major sediment production event integrates widespread mass wasting of slope-stored debris and sediment stored as headwater valley fill. This can increase sediment load within the channel system beyond stream carrying capacity, and deposition results. These deposits will subsequently be eroded and moved downstream.

In such a sedimentation sequence of production, deposition, and remobilization, sediment is temporarily retained in storage, but it eventually makes its way downstream, causing alternating episodes of deposition and erosion in stream channels.

## INVESTIGATIONS

This study was undertaken to investigate the effects of episodic sediment production on stream morphology in steepland drainage basins. Once a qualitative concept of sediment transport processes and a quantitative assessment of sediment storage changes had been made during a sedimentation sequence, a model of steepland sediment production and channel change in space and time can be designed.

Several researchers have noted a distinct zonation of bed sediment transport processes and channel and valley morphology along the longitudinal profile of a steepland drainage basin. O'Loughlin (1969), Kelsey (1977), and Hayward (1978) all described a three-zone system. In this system, the upper basin acts as a source of debris for downstream reaches and consistently tends toward a negative sediment mass budget. The middle of the basin acts as a conduit or transmitter of debris and maintains a relatively balanced sediment mass budget. The upper and middle zones feed sediment into the lower reaches where decreased channel gradient and broad valley floors commonly result in net sediment accumulation. Harvey (this volume) describes these same zones in an experimental drainage basin in the Rainfall Erosion Facility at Colorado State University.

Previous conclusions regarding changes in channel morphology and sediment transport in steeplands have been derived from short-term studies. To substantiate these hypotheses, long-term studies are required, unless a time-space substitution can be achieved. Rapidly eroding badlands provide an opportunity to do this. Some prerequisites for such an area are high relief, abundant bedload production, and sufficient runoff to transport bedload.

The Kraft Badlands in east-central Wyoming is an appropriate area in which to perform such a study. These badlands lie just north of Pine Ridge, the southern boundary of the Cheyenne River Basin, at 42$^{\circ}$58' north latitude and 104$^{\circ}$9' west longitude. The Kraft Badlands are typical of the area below Pine Ridge Escarpment where the Chadron and Brule Formations of the White River Group crop out. The rolling grassland of this region supports about 10 percent groundcover of mixed grass and sagebrush with grass predominating. Soils are thin and residual with no profile development. When the vegetation and soils are breached, badlands form in the underlying bedrock. The study area is underlain by a sandy-clayey siltstone of the Brule Formation. Sediment is produced from bedrock by shrink-swell weathering. This process fractures the siltstone into coarse sand and granule-size particles, which are then transported to headwater channels and lower-slope storage locations by winter winds and dry raveling. Sediment is stored at these locations until summer thunderstorms deliver it to the main channel network. This constitutes an annual sediment-production event. The badlands display all the characteristics of steepland basins: wide, braided valley fills; long straight slopes; high relief; and elongate drainages.

A detailed investigation was conducted in the Kraft Badlands in the summer of 1978.

## MORPHOLOGY AND PROCESSES OF STUDY BASINS

Preliminary studies revealed that three zones could be distinguished along the longitudinal profile of the study basins, as described in steeplands elsewhere (O'Loughlin 1969, Hayward 1978). Distinct breaks in valley morphology generally mark boundaries between the headwater, transitional, and lower braided zones--or, for simplicity, zones 1, 2, and 3, respectively. Zone 1 is separated from zone 2 by an abrupt increase in valley width and decrease in channel slope. Zone 2 terminates at zone 3, where valley width dramatically increases, usually where third-order tributaries join. Slope slightly increases at this point because of localized fan-building at the tributary junction.

Debris flows and debris torrents move sediment downstream through zone 1. Debris flows occur in steep first- and second-order streams, and scour bedrock. Mass failure is initiated when pore water pressures and rainfall intensities reach critical levels. Debris flows in the Kraft Badlands generally deposit steep fans at the first stream junction encountered; however, the flows may stop at any location within a channel. Debris torrents bring sediment down more gently inclined second- and third-order channels and deposit lobes of sediment in lower zone 1 and at the boundary between zones 1 and 2. Torrents are very wet slurries, similar to large flows described by Klock and Helvey (1976).

Below second- and third-order junctions, in zone 2, sediment moves as bedload in a braided channel confined between valley walls. At peak flows, the bedrock walls act as rigid boundaries. After an event with high bed-sediment flux, alternate reaches exhibit evidence of a raised channel bed in a regular fashion downstream. The spacing of these aggraded reaches corresponds with riffle spacings in pool-riffle streams (Keller and Melhorn 1978).

Valleys widen downstream and channels become permanently braided in zone 3. Energy is generally insufficient to transport continuously the quantity of material delivered during a storm event without temporary storage within the zone.

STORM PERIODS

Precipitation is used as a surrogate for runoff in this study. Storm characteristics during the study period are described in table 1. All storms were short-duration convective thunderstorms. Several consisted of a series of thunderstorms of various magnitudes which were associated with passing frontal systems. Four storm periods are distinguished beginning with May 27, 1978 (day 58) designated as the beginning of storm period 1 (table 1). The final column in this table signifies whether mass wasting of headwater channel stored sediment occurred only during storm periods 2 and 3 (table 1).

SEDIMENT BUDGETS FOR FIVE BASINS

Sediment production and yield were estimated or measured for basins 1100, 1200, 1300, 0200-0250, and 0300 (table 2; fig. 1). From these data, sediment-delivery ratios (SDR) were calculated.

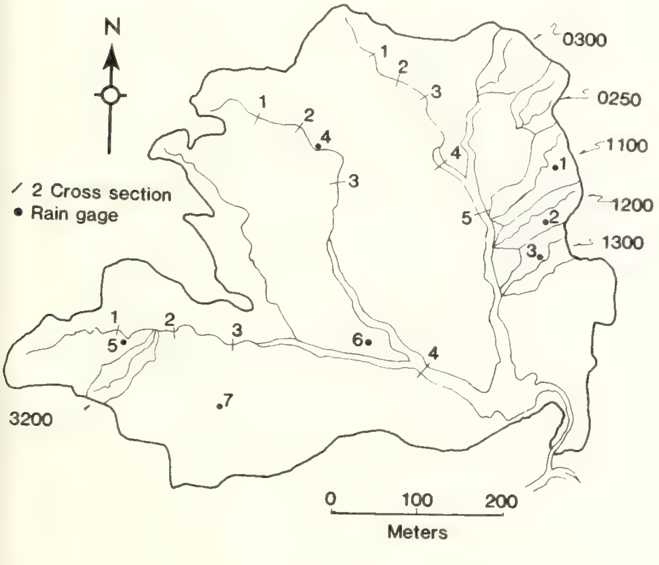

Figure 1.--Location of storage rain gages, tributary basins, and main drainages with cross sections in the Kraft Badlands, Wyoming.

The sediment-delivery ratio (SDR), the ratio of sediment yield to sediment production from hillslopes for the total basin, is usually less than 1.0. A value of unity occurs when all the material produced in the basin moves directly to the outlet or when erosion of downstream channel-stored sediment compensates for that sediment deposited upstream. Unity for the SDR then becomes the reference point from which net gain or loss from storage within the channel network can be quantified relative to sediment production.

A mass-balance equation was used to calculate sediment yield (Y) for the three storm periods. Assuming continuity of mass, yield can be calculated from the equation, $Y = P - \Delta S$, where $Y$ = yield, $P$ = production, and $\Delta S$ = change in storage along the main channel.

Sediment Delivery Ratios with Time

The sediment-delivery ratio (SDR) increased through time and with larger storms during the study (fig. 2). For storm period 1 (day 64, fig. 2), the basin 1100 SDR was greater than 1.0. Gross sediment volume transported was small relative to events in storm periods 2 and 3. Zone 3 alluvium was gullied and transported out of the drainage basin unaccompanied by headwater bed material production. After storm period 2, the SDR in basins 1200 and 1300 was less than in basins 0300 and 1100, all being less than 1.0 (fig. 2).

For period 3 storms, the most erosive storms of the study period (fig. 2), the SDR decreases for the low-relief basins (1100 and 0300), but increases for the high-relief basins (1200 and 1300). In all cases, the SDR is less than 1.0. Therefore, sediment delivery increased more rapidly--relative to main stream storage--in steep, deeply incised basins (high relief) than in less steep, more shallowly incised, low relief basins.

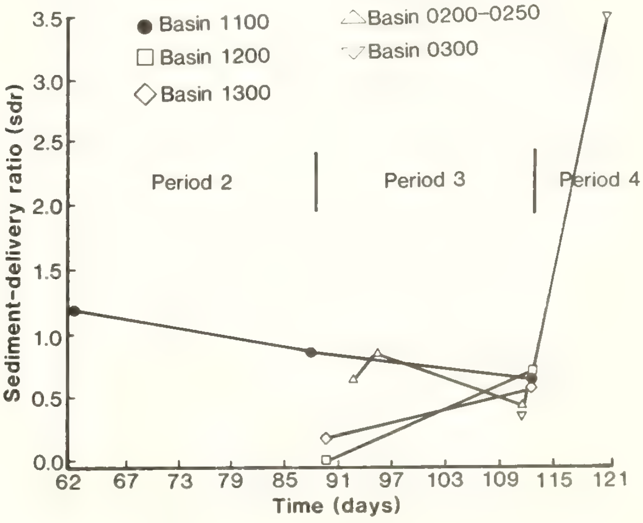

Figure 2.--Change of sediment-delivery ratios with time for five tributary basins.

Table 1--Precipitation data for period May 27, 1978 (day 58) to August 12, 1978 (day 134)

| Storm period | Date | Storm number | Peak rainfall intensity | Mass wasting of headwater channel sediment? |
|---|---|---|---|---|
| | | | cm/h | |
| | May 27 (day 58) | | | |
| 1 | | 1 | 0.2 | NO |
| 1 | | 2 | 0.5 | NO |
| | June 4 (day 64) | | | |
| 2 | | 3 | 0.5 | YES |
| 2 | | 4 | 0.5 | YES |
| 2 | | 5 | 1.0 | YES |
| 2 | | 6 | 1.0 | YES |
| 2 | | 7 | 0.2 | YES |
| 2 | | 8 | 2.3 | YES |
| 2 | | 9 | 1.5 | YES |
| | June 3 (day 94) | | | |
| 3 | | 10 | 2.0 | YES |
| 3 | | 11 | 0.5 | YES |
| 3 | | 12 | 0.2 | YES |
| 3 | | 13 | 0.5 | YES |
| 3 | | 14 | 20.6 | YES |
| | July 23 (day 114) | | | |
| 4 | | 15 | 1.5 | * |
| 4 | | 16 | 2.3 | * |
| 4 | | 17 | 0.5 | * |
| 4 | | 18 | 0.2 | * |
| | Aug. 12 (day 134) | | | |

*Headwater channel sediment storage completely depleted.

Table 2--Geomorphic characteristics of the six tributary basins

| Drainage basin | Relief, H | Basin length parallel to main stream | Length of main stream | Area, A | Total stream length, L | Drainage density, Dd=L/A |
|---|---|---|---|---|---|---|
| | Meters | Meters | Meters | Meters$^2$ | Meters | Meters/meters$^2$ |
| 0300 | 3.7 | 64.7 | 77.4 | 2512 | 489 | 0.19 |
| 0200 | 4.8 | 73.1 | 89.0 | 2097 | 492 | 0.24 |
| 1100 | 8.7 | 112.3 | 143.0 | 4574 | 867 | 0.19 |
| 1200 | 7.2 | 100.6 | 107.4 | 2662 | 492 | 0.18 |
| 1300 | 9.1 | 99.9 | 102.1 | 2661 | 658 | 0.25 |
| 3200 | 9.4 | 90.6 | 99.5 | 2031 | 444 | 0.22 |

ring storm period 4, the SDR increased amatically and again exceeded 1.0 in basin 00-0250. The main channel in zone 2 was the urce of transported sediment. This is similar period 1 in basin 1100. The difference in the gnitude of the SDR between periods 4 and 1 sults from the greater intensity and duration of orm 14 relative to period-1 storms.

e variability of main-channel storage and diment-delivery ratio over the study period thin an individual basin illustrates that ainage-basin morphology is not the only factor ntrolling these variables. For better derstanding of the great variability of eepland erosion and sedimentation implied by gure 2, the linkages between processes of oduction and transport themselves must be taken to consideration.

## ORPHOLOGY CHANGES AND SEDIMENT ROUTING

### eneral Description

asin 1200 is very similar to basins 1300 and 3200 fig. 3). Figure 4 shows the longitudinal profile or basin 1200. Headwater channels are steep, eep, narrow, and long, whereas channels in ones 2 and 3 are wider, flatter, and maintain ermanent alluvial fills. Snowmelt runoff incised n initial, sinuous channel in the alluvium of one 2. This channel shallowed and became iscontinuous in zone 3, and zone 1 was unaffected.

### ehavior During Storm Period 2

o storm runoff occurred during period 1, but eriod-2 storms were of sufficient magnitude and ntensity to initiate debris flows in headwater hannels. Debris torrents eroded the upper zone-1 ain channel to bedrock, and a large mass of ediment was delivered to the boundary between ones 1 and 2 (fig. 5). Sections of fill in the pper 20 m of channel in zone 1 were scoured uring period 2 (the July 4 survey).

t the boundary between zones 1 and 2, thalweg levation rose abruptly (fig. 5). A secondary eak at cross section 6 corresponded with an ncrease in valley width. Downstream from these eaks, the thalweg bed elevation rose above the riginal snowmelt channel elevation (fig. 6), but t did not reach the reference survey elevation, o a loss of elevation is recorded on figure 5.

ross section 7, 27 m downstream from the head of he channel, shows the deposition at the boundary etween zones 1 and 2 (fig. 7). The initial, -shaped fill inherited from winter accumulation till existed in the June 3 survey (fig. 7). uring period 2, debris-torrent deposition ncreased mean bed elevation 9.7 cm, the maximum ecorded increase in mean bed elevation throughout he study basin.

s sediment storage increased at cross section 7, he valley floor of zone 2 was reworked, and the nowmelt channel filled--with little change in ean bed elevation. Channel morphology changed to raided, with the channel covering about half the alley width.

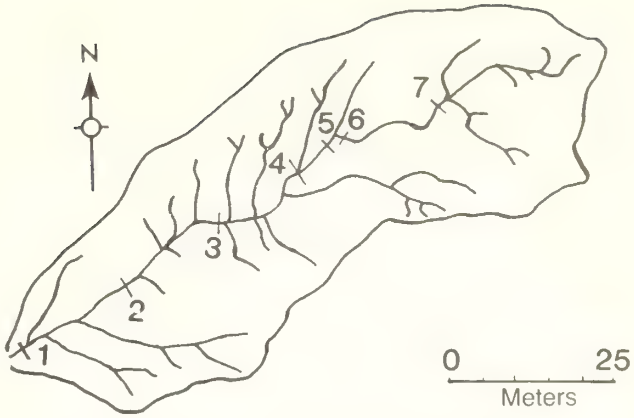

Figure 3.--Basin 1200 showing drainage divide, drainage pattern, and cross-section locations.

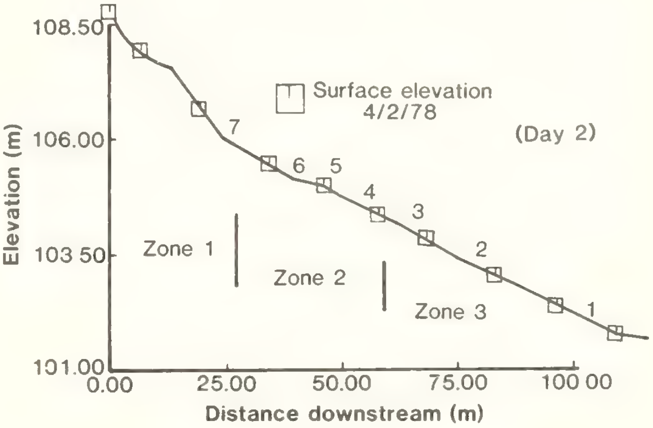

Figure 4.--Longitudinal profile of channel in basin 1200. Numbers refer to cross-section locations.

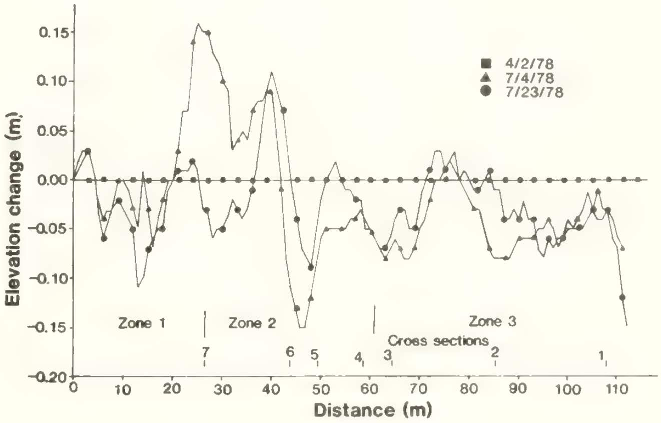

Figure 5.--Thalweg bed-elevation change relative to the April 2, 1978 valley floor (terrace) elevation, basin 1200.

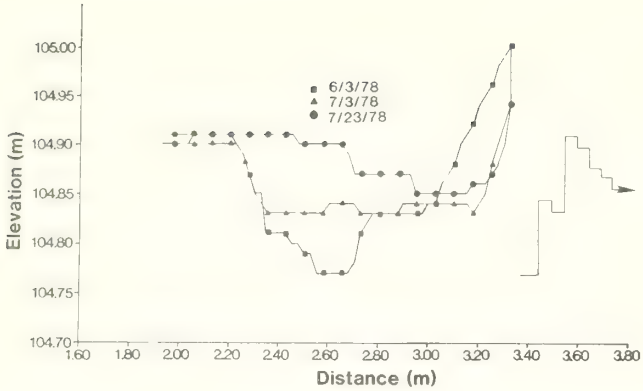

Figure 6.--Cross section 5, zone 2, basin 1200. Schematic diagram at the right illustrates channel-bed behavior during the study period.

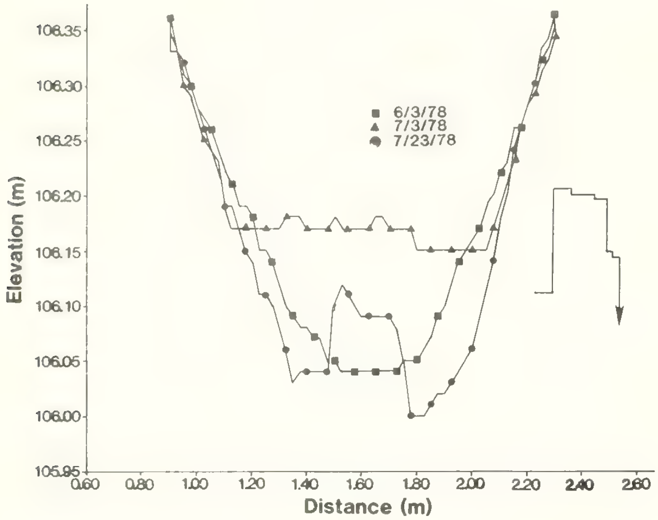

Figure 7.--Cross section 7, lower zone 1, basin 1200. Schematic at the right illustrates the behavior of the channel bed over the period of record.

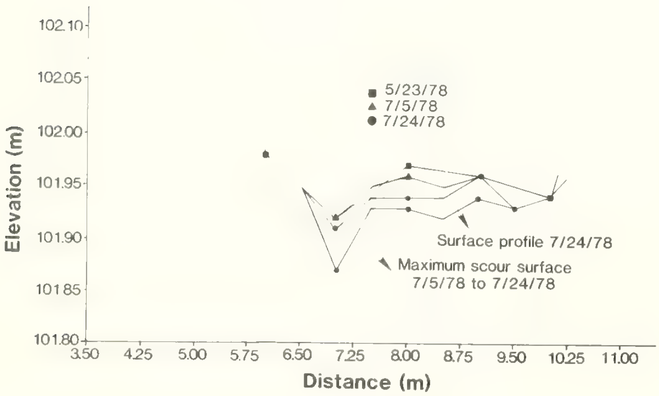

Figure 8.--Cross section 1, lower zone 3, drainage basin 1200. Lower profile for 7.24.78 is the surface of greatest scour during the survey interval. Upper profile for 7.24.78 is existing surface at time of survey.

During period 2, local filling of reaches of zone 3 (fig. 5) reflects the formation of fans in the channel. The profiles of cross section 1 (fig. 8) illustrate the trenching and subsequent reconstruction of an in-channel fan. Multiple channels incised the fill during storm period 2. This was followed by minor refilling, as documented by the surface profile on July 5 (fig. 8). During storm period 3 (July 24 survey), the greatest recorded incision was followed by channel filling and general valley aggradation as the fan began to rebuild.

Behavior During Storm Period 3

Period-3 storms moved the sediment stored at cross section 7 downstream (fig. 5), but the accumulation 40 m downstream from the channel head was not removed. This accumulation shifted downstream, filling and widening the channel below the point of valley widening at cross section 6.

During period 3, the channel at cross section 7 degraded to the level of the central terrace of the July 23 profile in figure 7. The channel then continued to incise, leaving this terrace and finally contacting bedrock at both valley sides. The overall changes in periods 2 and 3 were characterized by abrupt filling followed by incision (fig. 7). In contrast, the zone-2 channel filled during storm period 3 and subsequently retrenched a channel in a series of steps, forming unpaired terraces with an overall increase in sediment storage relative to the early June condition (fig. 6). Therefore, the two sections were out of phase in fluctuations of bed-sediment storage. In-channel fan building continued in zone 3.

## MODEL OF CHANNEL CHANGES IN BASIN 1200

Observations in basin 1200 provide a basis for describing the general behavior of the streambed during a sedimentation sequence.

### Zone 1 (Headwater Zone)

Figure 9 shows an idealized sequence of channel cross section development in lower zone 1. Winter sediment production produces the initial spring conditions of a U-shaped valley fill (line 1). Debris-torrent deposition abruptly aggrades the cross section (line 2). Precipitation on hillslopes of exposed bedrock yields flashy, sediment-free runoff, which erodes the deposit to the terrace level of line 3. Subsequent late-storm streamflow further incises the remaining deposit, forming a valley-side terrace. This illustrates an excess of transport energy relative to sediment availability in zone 1.

### Zone 2 (Transition Zone)

Over the same sedimentation sequence, the zone-2 channel fluctuates by eroding initially and then shifting between aggrading and retrenching. Discontinuous terraces and bars characterize the initial fill (line 1, fig. 9). Storms that precede sediment production from zone 1 discontinuously incise a narrow channel and

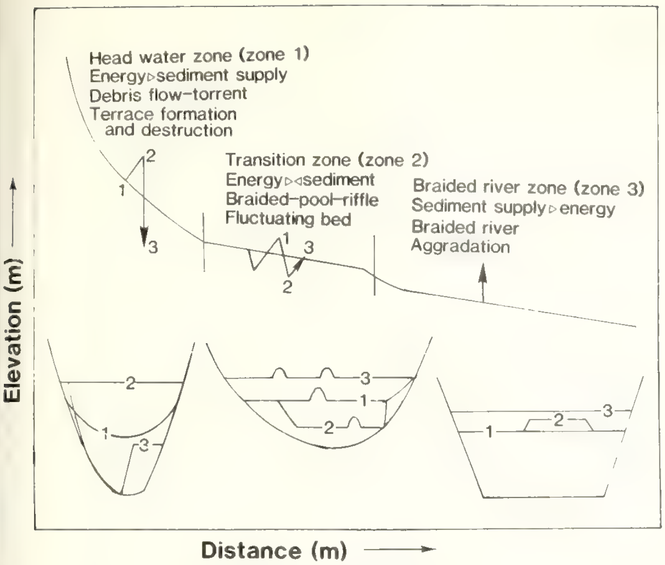

Figure 9.--Idealized longitudinal profile divided into headwater, transitional, and braided zones. Arrows denote mean behavior of bed through a sedimentation cycle. Cross sections correspond to each zone over time, progressing from 1 to 3.

produce multiple, paired or unpaired terraces. As bed sediment produced in zone 1 is transported through zone 2, the bed elevation rises and flow covers the entire valley floor. That is, during a series of major runoff events that follow a major upstream sediment production event, valley bed sediment storage temporarily increases. Scour of recently deposited sediment occurs after sediment delivery from zone 1 ceases, yet runoff events continue.

Zone 3 (Lower Braided Zone)

In zone 3, mean bed elevation tends to increase with time during a sedimentation sequence. The general trend is for material to shift from the headwaters to zone 3 and to be stored there for periods exceeding a year under moderate hydrologic conditions. Only during the largest hydrologic events did basins produce runoff and transport sediment throughout the three zones. During smaller storms (period 1), when zone 1 and zone 2 or both were actively producing and transporting material, zone 3 received little flow capable of modifying the valley fill. The time available to produce bed changes in zone 3 was limited during the summer storm season. Duration of runoff was very important. Zone 3 acts as a sink for sediment until a sufficiently large hydrologic event causes transport in zone 3.

Bar formation and general aggradation in discrete reaches form fans. Beginning at line 1 (fig. 9), channels incise and possibly widen to encompass most of the valley width when water and bed-sediment discharge are low. These channels quickly fill when bed-sediment discharge increases and in-channel fan building begins. Bars build and coalesce (lines 2 and 3, fig. 9) until the entire valley floor is raised. Trenching through the fan by headward extension of a trench should eventually remove most of this deposit.

SUMMARY

In steep terrain, as exemplified by the Kraft Badlands, sediment production is not uniform in time or space. A sediment production, deposition, erosion sequence occurs when large quantities of coarse sediment are episodically produced and delivered to the channel network in steepland drainage basins. Widespread mass wasting of slope and channel-stored material produces large quantities of sediment that are progressively delivered to the main stream. Transport capacity of the channel network is overloaded by a production event and a sequence of channel filling and erosion downstream ensues.

Three zones along the longitudinal profile were recognized: (1) headwater, (2) transition, and (3) lower braided zones. Different bed-sediment transport processes and resulting channel and valley forms characterize each zone.

The zones within a basin are usually out of phase with one another. Zone 2 initially acts as a source of sediment while zone 3 acts as a sink. As zone 1 begins to produce sediment, zones 2 and 3 fill. Finally, zone 2 acts as a conveyor of material temporarily stored at the boundary between zones 1 and 2, and zone 3 acts as both a sink and source of sediment as in-channel fans build and erode. Bed-sediment availability at the basin outlet increases late in this sequence. Therefore, sediment yield measured at the basin outlet from a storm of given magnitude varies greatly, depending on when the storm occurs relative to channel-bed changes upstream.

Of great significance is the large magnitude of the changes, and their nonuniformity in time. This suggests that engineering structure designs based on short-term records of sediment yield and existing channel morphology in steepland basins may prove to be inadequate.

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# Sediment Budget of a Small Coast Range Drainage Basin in North-Central California

Andre K. Lehre

ABSTRACT

Detailed measurements of erosion and sediment discharge in the drainage basin of Lone Tree Creek, a 1.74-km$^2$ drainage 14 km northwest of San Francisco, showed that landslides in colluvium-filled swales are the most important erosional agent and account for most of the sediment yield from the drainage basin. The bare scars act as loci for sheetwash and gully development; they refill by backwearing of slide scarps and by soil creep. During the study period, only 53 percent (2068 t/km$^2$) of all sediment mobilized was discharged from the basin; the remainder was stored in slide scars, on foot slopes, and in gully and channel banks and beds. Sediment is removed from storage by storms with recurrence intervals greater than 10 years. Comparison of current rates of landsliding and scar filling suggests that colluvium is currently being stripped and that the rate of sliding has increased approximately tenfold in the last 100 years.

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Andre K. Lehre, Research Associate, Department of Geological Sciences, University of Washington, Seattle, Washington 98195. Presently at: Department of Geology, Humboldt State University, Arcata, California 95521.

## INTRODUCTION

The sediment budget of a drainage basin is a quantitative statement of relations between sediment mobilization and discharge, and of associated changes in storage. Such budgets are useful for land management and are a first step in understanding landscape evolution. Proper formulation of a sediment budget requires: identification of erosional processes and understanding of their controls and interrelations; measurement of magnitude and frequency of sediment mobilization by each process, and of sediment discharge from the drainage basin; and identification of sediment-storage elements and quantification of the volume, residence time, and changes in volume of stored sediment. Of particular interest are the circumstances under which material is removed from or added to storage.

Erosional processes in steepland drainage basins of the California Coast Range are complex, involving sliding, soil creep, gullying, sheetwash, and channel-bed and bank erosion. Detailed studies are few. This paper reports results of 3 years of measurements in a small, mountain drainage basin north of San Francisco and the model of process linkages they suggest.

## THE DRAINAGE BASIN

### Location and Land Use

Lone Tree Creek is a small, steep, relatively undisturbed drainage basin in the California Coast Range about 14 km northwest of San Francisco. It lies on the southwest slope of Mt. Tamalpais and drains directly to the Pacific Ocean. Study was restricted to the 1.74 km$^2$ upstream of Highway 1, an area including the drainages of Main Lone Tree Creek (MLTC) and South Branch (SOBR) (fig. 1). The drainage basin was grazed by cattle from the mid-1800's until 1967, when it was incorporated into Mt. Tamalpais State Park. Today it is used only by occasional hikers.

### Geology

The drainage basin is underlain by greywacke melange of the Franciscan Assemblage (Blake et al. 1974), consisting predominantly of a matrix of sheared and locally comminuted greywacke and shale embedded with isolated blocks of hard coherent greywacke and "exotic" blocks of greenstone, chert, altered rhyolite, and metamorphic rocks. These blocks or "knockers" range from 0.3 to 150 m across. The broken and weathered greywacke matrix is exposed only in stream channels, some landslide scars, and as barren, steep-fronted steps on hillslopes and ridgecrests.

### Topography

Lone Tree Creek drains narrow, steep-walled canyons separated by gently rounded upland ridgecrests (fig. 1). Average channel slopes range from 15 percent on MLTC to 36 percent on some tributaries. Upland slopes range from 5 to 30 percent. Valley side-slopes are 35 to 85 percent and tend to be convex or straight in profile and strongly convex in plan. Most hillslopes are indented by shallow swales spaced 30 to 150 m apart across the slope. These topographic hollows are typically 60 to 90 m long and 30 to 60 m wide. Upslope and at their heads, swales are U-shaped and lack a defined channel; downslope, some remain U-shaped, without a channel, but many become narrowly V-shaped and merge into a gully at their lower end. Soil augering and exposures in gullies and landslide scars reveal that the U-shaped portions contain from 1 to 5 m of colluvium filling a U- or V-shaped hollow scoured in bedrock. Bedrock is often exposed at the downslope end of the swale, particularly if it narrows and becomes a gully. Similar features have been observed elsewhere in California (Wahrhaftig 1974, p. 87) and Oregon (Dietrich and Dunne 1978). Swales carry runoff during heavy winter rains and are the first-order drainages of the basin. They are also the main loci of landsliding and hillslope gullying.

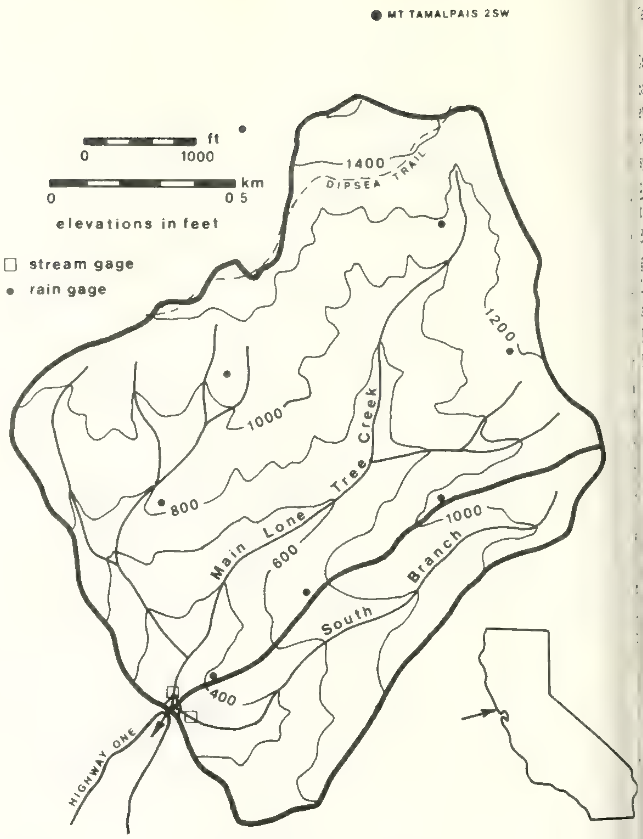

Figure 1.--Lone Tree Drainage Basin.

Including first-order tributaries mapped on air photos and in the field, the drainage basin contains 10.8 km of channels. Drainage density is 6.21 km/km$^2$. Relief ratio is 190 m/km.

### Vegetation

Grassland covers about 50 percent of the drainage basin. It occupies chiefly ridgecrests and exposed upper and west-facing slopes. Brushland, composed primarily of rabbitbrush (Baccharis spp.), sage (Artemisia spp.), and poison oak (Rhus diversiloba T. & G.), covers about 30 percent of the basin. It occupies the steeper, rockier, drier slopes and lies most typically between grassland and the forest of the canyon bottoms. Local concentrations of brush also occur in and along the lower portions of many gullies draining landslides. Forest occupies most of the valley bottom and north-facing slope of MLTC and the bottoms and lower slopes of its tributaries in the upper half of the basin. In the lower half of the drainage basin, forest consists mainly of California laurel (Umbellularia californica (H. & A.) Nutt.), some oak (Quercus spp.) and tanoak (Lithocarpus densiflorus (H. & A.) Rehd.), and infrequent Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco); in the upper half, forest is mostly 30- to 50-year-old Douglas-fir and Laurel. Understory is usually either dense bracken fern or nearly nonexistent.

### Climate and Hydrology

Lone Tree Creek has a Mediterranean climate moderated by sea-fog which blankets much of the basin in summer. Mean annual rainfall is 865 mm (Rantz 1971), about 90 percent of which falls between November 1 and April 30. The abrupt rise of the basin from 61 m at the outlet to 427 m at its head 1.9 km away produces strong orographic effects. Data from eight gages in the basin show that rainfall at the outlet is only half that received at Mt. Tamalpais 2SW, a U.S. Weather Service gage 0.4 km north of the basin head.

Rainfall intensities measured at Mt. Tamalpais 2SW from October 1971 to September 1974 exceeded 5 mm hour less than 5 percent of the time. Regional depth-duration-frequency relations (Rantz 1971) indicate that intensities of 25 mm/hour have a 15- to 20-year recurrence interval. Ninety-five percent of 24-hour rainfalls are less than 65 mm. The maximum 1-hour rainfall during the study was 20 mm on January 12, 1973, which also produced the maximum 24-hour rainfall of 165 mm. These represent the wettest day of a very wet year and were associated with a 15- to 20-year flood (Lehre 1981).

Total annual precipitation may differ by a factor of 2 in successive years. Based on the 34-year record at the nearby Muir Woods gage, the 3 study years 1971-72, 1972-73, and 1973-74 rank 22, 3, and 4, respectively, in terms of total annual rainfall. Although the rainfall totals for 1973 and 1974 are similar (table 1), the 1974 rainfall was spread more evenly over the rainy season.

Mean annual runoff of Lone Tree Creek, estimated through several methods (Rantz 1967, 1974; Crippen and Beall 1971), is about 330 mm or about 38 percent of estimated mean annual precipitation. For the study period, runoff ranged from 34 to 74 percent of annual rainfall (table 1). Runoff produced by individual storms of similar size ranged from 2 to 94 percent of rainfall, depending on rainfall intensity and antecedent precipitation.

During and immediately after large storms, overland flow occurs down the center and lower slopes of most grassland swales; these areas may remain saturated or nearly so for several days after a storm. Overland flow also occurs on bare soil in landslide scars and in saturated zones immediately adjacent to stream channels. The openness and unrilled appearance of forest litter suggest that overland flow is relatively unimportant there. The proportion of drainage basin contributing direct runoff in storms, estimated by the technique of Dunne et al. (1975), increases from 1 to 3 percent in light storms to 25 to 33 percent in heavy ones and on SOBR approached 70 percent in the storm of January 12, 1973.

## HYDROLOGIC INSTRUMENTATION AND DATA COLLECTION

Long-term precipitation data are available from two nearby U.S. Weather Service gages, Mt. Tamalpais 2SW (recording) and Muir Woods (nonrecording). Eight cans installed as gages at several elevations within the basin were read after major storms.

Streamflow was measured at staff gages on MLTC and SOBR near Highway 1 (fig. 1). A crest-stage gage at the MLTC site and an auxiliary staff gage at the inlet of the highway culvert permitted indirect measurement of flood flows. From October 1971 to October 1974, gages were read at 5-minute to 6-hour intervals during nearly all major storms and about half of the minor ones.

Table 1--Annual rainfall, runoff, and water loss for water years 1972-74 on Lone Tree Creek

| Water year | Rainfall | Runoff | Water loss | Runoff, as % of rainfall |
|---|---|---|---|---|
| | ------------Millimeters | ------------ | ------------ | |
| 1972 | 602 | 206 | 396 | 34 |
| 1973 | 1184 | 874 | 310 | 74 |
| 1974 | 1046 | 770 | 277 | 74 |
| Average for period | 945 | 617 | 328 | 65 |

Suspended-sediment and dissolved-solids concentrations were determined from depth-integrated samples taken at the gaging sites using a DH-48 sampler (Guy and Norman 1970). Time between successive samples in a storm ranged from 5 minutes to 6 hours. A total of 184 samples were taken on MLTC, 172 on SOBR, and 79 on their combined flow. Of these, 30 on MLTC and 29 on SOBR were analyzed for total concentration of dissolved solids. Sediment concentrations were determined by procedures outlined by Guy (1969). A very small number of bedload samples (six on MLTC, one on SOBR) were taken with a hand-held Helley-Smith bedload sampler. High velocities, high turbidity, large bed-particle sizes, and time constraints made bedload sampling generally impractical. Bedload estimates are thus uncertain.

## WEATHERING, SOIL, AND COLLUVIUM

Weathering in the drainage basin is dominantly chemical. Rainwater penetrating joints and fractures in the greywacke bedrock reacts with feldspars and unstable dark minerals to form illite, vermiculite, and random mixed-layer clays (Schlocker 1974). The end product is a rock residue of silty sand or sandy silt containing from 10 to 85 percent gravel-size (2- to 150-mm) clasts of less-weathered bedrock. Its bulk density is 1.45 to 1.9 g/cm$^3$ compared to 2.4 to 2.65 g/cm$^3$ for unweathered rock.

Weathered rock becomes colluvium through mixing and downslope transport by processes both biological (burrowing, root growth, tree fall) and physical (creep, sliding, sheet erosion, gullying). Colluvium forms the parent material of many drainage-basin soils.

Drainage-basin soils are generally thin (except in swales), stony, and poorly developed. Texturally, both soil and colluvium are stony or very stony silt loams (20 to 80 percent fragments larger than 2 mm). Soil clay content in the less than 2-mm fraction is 15 to 25 percent. Soil bulk density under grass cover ranges from 1.15 to 1.5 g/cm$^3$.

Soil and colluvium thicken dramatically from less than 0.6 m on divides between swales to 1.3 to 5 m in swale centers. This colluvium commonly contains local concentrations of coarse gravel aligned subparallel to either the bedrock or ground surface; surface wash and rilling produce nearly identical concentrations of gravel on the surface of present-day scars. Downslope elongation of weathered and fractured bedrock blocks contained in the colluvium, together with short, crude stone lines extending downslope from bedrock irregularities, suggest differential shear or creep. Surface creep is suggested by the dark, overthickened (0.6 to 1.6 m thick), apparently cumulative A-horizon of soils in grassland swale centers. In recent slide scars, dark topsoil accumulates below eroding scarps and is spread downslope by wash and creep.

Landslides and gullies on hillslopes are restricted almost entirely to swales. These contain all ages of landslide scars, from fresh, raw scars to old, nearly filled and totally revegetated ones visible only at low sun angles. From these observations, I interpret the swales as the product of infrequent landslides and gullying, and their colluvial fills as the result of subsequent creep, scarp-backwearing, surface wash, and (sometimes) slides upslope. Slide debris either enters channels directly or is stored on hillslopes below the scar.

## A MODEL OF PROCESS RELATIONSHIPS

The first step in making a sediment budget for a drainage basin is to identify the processes mobilizing sediment, their relations, and their controls. Dietrich and Dunne (1978) have done this for a forested western Oregon drainage basin. Like theirs, the model proposed below for Lone Tree Creek involves filling and episodic evacuation of swales; it differs, however, by the inclusion of gullying and in the importance assigned to sheet and scarp erosion. Evidence for the model is discussed in detail in Lehre (1981).

### General Erosion Model

Erodible material in the drainage basin--weathered rock, soil, colluvium, and alluvium--resides in four storage elements: swales, hillslope mantle outside of swales, channel and gully banks, and channel bed. In a gross sense, erosional processes can thus be divided into those acting primarily to move sediment from point to point on hillslopes, and those that mainly transfer sediment from the hillslopes to the channel system or from one part of the channel system to another. Linkages between storage sites and transfer processes are diagramed in figure 2.

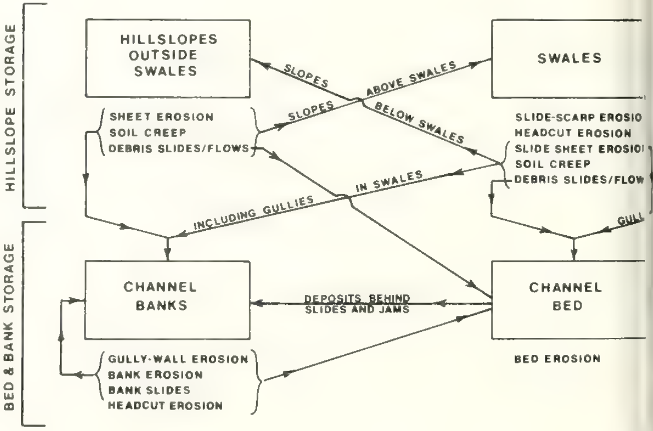

Figure 2.--General linkages between sediment-storage sites and erosional processes. Boxes indicate storage elements; listed below each box are erosional processes mainly responsible for mobilizing sediment in that element. Arrows show transfers between elements. Labels on arrows qualify or restrict location of transfers.

Swales are initiated when weathered rock fails as a debris slide, leaving a long, scoop-shaped depression. Sheet erosion and rilling begin operating on the floor of the scar, winnowing out fines and leaving a gravel lag. Water concentrated by the scar may initiate a gully downslope, which works headward and joins the scar to the channel system. The gully commonly widens and deepens significantly after connection to the scar. Sediment is contributed to scar and gully by spalling, sliding, and sheet erosion of their scarps; the gully also receives sediment eroded from the scar upslope. Soil creep on adjacent slopes helps replenish the eroding scarps. Within the scar, sediment is redistributed by surface wash, rilling, dry sliding, and creep. Much of the debris entering the gully is deposited either in a fan downslope (if the gully is discontinuous) or in the bed of the channel system.

Filling of the swale begins as coarse lag accumulates in rills and gully, forcing more water to infiltrate and move as subsurface flow. At the same time, shrubs and grass toppled in from scarps become established and stabilize the accumulating debris. Filling increases as erosion in scar and gully-bottom are reduced. With sufficient filling and revegetation, scarp erosion slows and rate of filling declines. Ultimately, scar and gully are healed, producing a smooth, U-shaped, colluvium-filled swale. Soil-water seepage and subsurface stormflow drain toward the swale axis, increasing moisture content and favoring production of saturation overland flow and high pore pressures in the swale center. The colluviul fill is gradually destabilized as it is thickened by continued creep and weakened by weathering (abetted by high moisture content). Finally, the colluvium fails in a heavy rainstorm, scouring the weathered bedrock, and the whole process begins over.

Sediment transported downslope out of swales by sliding either enters a channel directly, where it is usually entrained by stormflow, or is deposited on the slope below and returns to hillslope storage.

Sediment in storage on hillslopes outside of swales is transported downslope by creep (including dry sliding and burrowing), surface wash, and, less commonly, by landslides. It ultimately enters the channel system through gully, bank, or headcut erosion. Most sediment in this element represents material weathered in place or involved in slow downslope transport. Locally, usually below swales, slide and gully deposits may cause large accretions to hillslope storage.

All sediment not transferred directly from hillslopes to the channel system by debris flow or gully transport must enter channels by erosion of channel banks, gully walls, and headcuts. Although this erosion is actually accomplished by sheetwash, scour, spalling, and sliding, it is more useful to consider only (with the exception of large bank slides) their combined effect. Thus figure 2 lists as the transfer processes gully-wall erosion, headcut retreat, bank erosion, and bank slides. Sediment mobilized by these processes is transferred to the channel bed or redeposited lower on channel banks.

Material reaching the channel bed is either removed immediately from the drainage basin as bedload and suspended load, stored temporarily as bars and channel deposits, or converted to bank deposits through accumulation behind a slide deposit or debris jam.

## PROCESSES AND PROCESS MEASUREMENT

The second step in creating a sediment budget is quantifying the contributions from each erosional process. In this section, each process is briefly discussed, together with the means used to measure its rate. Here I use "sediment mobilization" to mean total amount of sediment moved any distance by a process, "sediment production" to mean the amount of mobilized sediment reaching or given access to a channel, and "sediment yield" to designate the amount of sediment actually discharged from the drainage basin. Note that sediment production by a process can never exceed mobilization by that process. Yearly mobilization and production for each process are listed in table 2.

### Hillslope Failures

Landslides occupy 2.7 percent of basin area and are the most conspicuous erosional features in the drainage basin. I mapped scars into three categories: raw (more than 80 percent unvegetated), recovering (10 to 80 percent unvegetated), and healed (less than 10 percent unvegetated). I identified a total of 404 individual scars, of which 320 (68 raw, 158 recovering, 94 healed) are on hillslopes, chiefly in swales; the remaining 84 (28 raw, 35 recovering, 21 healed) occur on channel banks. Most hillslope slides occur in grass and brush; only five were identified in forest.

Hillslope failures are almost exclusively debris slides and flows. Failure occurs during heavy rains, either on the bedrock-colluvium contact or above a denser or more clay-rich layer in the colluvium. During the study period, 29 slides were triggered by the storm of January 11-12, 1973, when 165 mm of rain fell in 24 hours, producing a 15- to 20-year flood. In the storm of March 31-April 1, 1974 (115 mm/24 hours, producing a 2- to 3-year flood), only two landslides occurred, both in swales undercut in 1973 by small, discontinuous gully heads. The high percentage of debris reaching channels in 1973 (53 percent) and 1974 (68 percent) (table 2) reflects the great fluidity of the debris flows and, to a much lesser extent, proximity to channels. Unlike the debris torrents reported in Oregon and northern California (e.g., Pierson 1977), these debris flows are not highly erosive. They commonly pass over grass and through brush with little damage; I attribute this to their high clay and water content.

Table 2--Sediment mobilization and production from individual processes in Lone Tree drainage basin

| Source | 1971 - 1972 |  | 1972 - 1973 |  |
|---|---|---|---|---|
|  | Mobilization (on slopes) | Production (reaching channels) | Mobilization (on slopes) | Production (reaching channels) |
|  | Metric tons/$km^2$ |  |  |  |
| Landslides | 0 | 0 | 1049 | 559 |
| Slide scarp erosion | 34 | 21 | 59 | 37 |
| Slide scar sheet erosion | 20 | 15 | 76 | 59 |
| Headcut erosion | 22 | 20 | 25 | 24 |
| Soil creep | 6* | Included in gully-scarp erosion | 6* | Included in gully-scarp erosion |
| Hillslope sheet erosion | 4* |  | 4* |  |
| Gully-scarp erosion |  | 82 |  | 194 |
| MLTC bank erosion |  | 8 |  | 20 |
| Bed erosion |  | 2 |  | 92 |
| Total | 86 | 148 | 1219 | 985 |
|  | 1973 - 1974 |  | 1971 - 1974 average |  |
| Landslides | 1795 | 1223 | 948 | 594 |
| Slide scarp erosion | 41 | 26 | 45 | 28 |
| Slide scar sheet erosion | 107 | 84 | 68 | 53 |
| Headcut erosion | 7 | 6 | 18 | 17 |
| Soil creep | 6* | Included in gully-scarp erosion | 6* | Included in gully-scarp erosion |
| Hillslope sheet erosion | 4* |  | 4* |  |
| Gully-scarp erosion |  | 201 |  | 159 |
| MLTC bank erosion |  | 20 |  | 16 |
| Bed erosion |  | 15 |  | 37 |
| Total | 1960 | 1575 | 1089 | 904 |

*Indicates effective mobilization. Effective mobilization, computed as (total length of channel banks in drainage basin) X (mobilization rate per unit width of slope), gives rate at which sediment can be supplied to channel banks by processes acting continuously over drainage-basin hillslopes. In contrast, total mobilization (sediment moved any distance) by such processes is given by (thickness of moving layer) X (total area affected by process) and is independent of downslope transport velocity.

Sequential comparison of aerial photos taken in 1952, 1965, and 1973, together with a volume-area relation for the scars, yields an average 22-year rate of sediment mobilization by sliding of 525 t/$km^2$ per year. Most of this sliding occurred in the storms of December 1955-January 1956, which produced 100-year flooding in most of northern California.

In an attempt to estimate long-term slide erosion rates, I have assumed arbitrarily that all raw and recovering landslides are under 100 years old. Their aggregate volume, divided by 100, yields a long-term slide mobilization rate of 187 t/$km^2$ per year. This rate is 7 to 10 times larger than rates reported from the Oregon Coast Range (Dietrich 1975, Swanson et al. 1976, Pierson 1977), 2.5 to 3.5 times rates in the western Oregon Cascades (Morrison 1975, Swanson and Dyrness 1975), and about one-sixth of the minimum 80-year rate in the San Gabriel Mountains of southern California (data of Rice et al. 1969 and Rice and Foggin 1971).

## Slide-Scarp Erosion

Slide scarps erode through spalling, sliding, and sheetwash. I obtained measurements of scarp backwearing from 149 sets of stakes installed around 14 raw or recovering landslides. Each set consists of two survey stakes driven to define a line approximately normal to the scarp. A steel tape was used to measure the distance along this line from the outer stake to the scarp; measurements are accurate to 5 to 10 mm. Stake-scar distances were remeasured after the rainy season. Retreat was converted to volume by multiplying by scarp height.

Retreat rates at individual stakes ranged from 0 to 240 mm in a single year. The 3-year mean retreat rate (all stakes) was 20 mm/year, equivalent to an average volumetric rate of 0.014 $m^3/m$ per year. Standard error ($s_e$) of the retreat rate is 2 mm/year. Mobilization was computed by multiplying the volumetric rate by total length of slide scarps in the drainage basin; this yields a 3-year total of 233 t.

Sediment production from landslide scarp-retreat is substantially less than mobilization for two reasons: about 40 percent of total scarp length surrounds slides not connected to the drainage net; and some unknown, but probably large, proportion of the mobilized sediment does not find its way directly to a channel but rather remains temporarily or permanently in the scar. An upper bound on sediment production can be calculated by subtracting from total mobilization the mobilization occurring in scars unconnected to the drainage net (table 2).

### Slide-Scar Sheet Erosion

Sheet erosion in slide scars is caused by sheetwash, rainsplash, micromudflows, and rilling. I measured this process with 173 nail-and-washer erosion pins (Emmett 1965) installed in six landslide scars. Average erosion in rilled scars was 5 mm/year ($s_e$ = 1 mm/year); in unrilled slides it was 2 mm/year ($s_e$ = 0.7 mm/year). Mobilization is calculated by multiplying bare slide area by the appropriate pin-erosion rate. In making this calculation, I assumed that "raw" slides contributed from 100 percent of their area, but "recovering" slides contributed from only 50 percent. "Healed" slides were ignored. Total sediment mobilized from 1971-74 was 353 t. An upper bound on sediment production is given by subtracting from this total the mobilization occurring in scars unconnected to the channel system (table 2).

### Headcut Retreat

Headcut retreat was measured with 58 stake sets installed around 19 headcuts. Average retreat rate for the 3-year period was 140 mm/year ($s_e$ = 26 mm/year), corresponding to an average volumetric rate of 0.041 $m^3/m$ per year. Applying this to the total length of headcuts in the drainage basin yields 3-year sediment mobilization of 18 $t/km^2$ per year. Adjusting this for headcuts in scars not connected to channels yields net production (table 2).

### Soil Creep

Soil creep on drainage-basin hillslopes is being measured by 102 creep test-pillars consisting of columns of 25-mm-long, 10-mm-diameter wooden dowel segments injected vertically into the soil through a 13-mm-diameter metal tube. Depending on soil depth and stoniness, pillar lengths range from 0.6 to 1.1 m. Creep is measured by excavating a pit next to the pillar and measuring offsets from the original line of insertion, defined by the lowermost pillar segments. Uncertainty in original insertion angle is $\pm 0.5^\circ$. Note that this technique measures only shallow soil creep and can yield only a minimum estimate of creep rate.

One pillar in forest and one in grass were excavated in 1974, 2 years after insertion. Rates at both sites are similar, but results are ambiguous because of the half-degree insertion uncertainty. They averaged a minimum of 0.5 and a maximum of 1.1 mm/year over a depth of 0.4 m, corresponding to volumetric rates of 0.0002 and 0.0004 $m^3/m$ per year, respectively. Applying these maximum rates to all slopes bordering channels in the drainage basin yields a yearly effective mobilization of 5.3 to 12.2 $t/km^2$ (see note, table 2). Because creep rates are certainly not uniform over the drainage basin, the error in this estimate is large.

In grassland, creep caused by vole burrowing is locally important, especially in swales. Although this creep affects only the upper 0.15 m of soil, measurements of tunnels and debris piles yield volumetric rates of 0.0001 to 0.006 $m^3/m$ per year (Lehre 1981). Assuming 10 percent of the grassland is burrowed (visual estimate), and using an average rate of 0.002 $m^3/m$ per year, about 3 $t/km^2$ per year is mobilized by voles.

### Hillslope Sheet Erosion

I estimated sheet erosion on hillslopes by means of 53 erosion pins installed on both well-vegetated and poorly vegetated grassland hillslopes. No pins were installed in brush or forest. Over 3 years, most pins showed either no erosion or slight net deposition; the pattern of erosion and deposition suggests hillslope sheet erosion takes place as rainsplash-driven creep of a layer about 1.5 mm thick (Lehre 1981). To calculate the corresponding sediment mobilization, I have assumed the sheet moves downslope 0.1 m/year--a volume flux of 0.000 15 $m^3/m$ per year. Applying this rate to all slopes bordering channels yields an effective mobilization estimate of 4 $t/km^2$ per year (see note, table 2). Although this rate is certainly incorrect in detail, I believe it reflects the proper order of magnitude.

### Gully Scarp Erosion

Erosion of gully side-scarps and walls, excluding headcuts, was measured with 133 stake sets arrayed about 12 gullies. Average retreat of raw gully walls for the period 1971-73 was 101 mm/year ($s_e$ = 12 mm/year); that of vegetated walls was 37 mm/year ($s_e$ = 6 mm/year). Corresponding volumetric rates are 0.033 $m^3/m$ per year and 0.0096 $m^3/m$ per year. These rates are significantly different at the 5-percent level. Assuming that the ratio of raw to vegetated walls in this sample is representative for the drainage basin, the combined weighted average rate of 0.013 $m^3/m$ per year multiplied by the total length of gully walls in the drainage basin yields a total mobilization and production of 833 t for 1971-74, or 160 $t/km^2$ per year.

### MLTC Bank Erosion

Bank erosion on MLTC could not be measured directly. The height (average 2.5 m) and indefinite edge of most of its banks prevented use of scarp-retreat stakes, and monumented cross sections were prohibited by limitations of time, staff, and equipment. Instead, bank erosion was estimated by comparison of two traverses of the channel, one at the beginning and one near the end of the study. During the first traverse, all bank slides were mapped. In the second traverse, all slides were again mapped, and volumes of new sliding determined. I also examined channel banks for evidence of fresh spalling, sliding, and undercutting (e.g., vegetation and moss trim lines; exposed roots; overhanging root mats, raw grooves) and estimated the volumes removed. On this basis, the average volumetric erosion rate of MLTC banks is 0.011 $m^3/m$ per year, and the total 1971-74 erosion is 82 t. I believe this estimate is within 50 percent of the true amount.

Table 3--Sediment and dissolved-solids yield of Lone Tree Creek. See text for discussion.

|  | 1971-72 | 1972-73 | 1973-74 | Average 1971-74 | Estimated long-term average |
|---|---|---|---|---|---|
|  | ----------Tons/km$^2$--------- |  |  | Tons/km$^2$ per year |  |
| Suspended load | 17 | 1227 | 576 | 607 | 180 |
| Bedload | 7.1 | 193 | 54 | 85 | 34 |
| Total particulate | 24 | 1420 | 630 | 692 | 214 |
| Dissolved load | 16 | 50 | 48 | 38 | 23 |
| Total denudation | 40 | 1470 | 678 | 730 | 237 |

### Bed Erosion

The largest uncertainty in this study is the amount of sediment that either entered or was removed from bed storage by aggradation and degradation of channels within the drainage basin. Ideally, these amounts could be determined by surveying a large number of monumented cross sections spaced at regular intervals along MLTC, SOBR, and major tributaries. This was impossible in the study. As a poor expedient, I have assumed that erosion and deposition measured at the MLTC and SOBR gaging sites are applicable to all alluvial reaches of those channels. Although this is certainly in error (see Lehre 1981 for discussion), the resulting estimates may suggest the proper order of magnitude. With this proviso, total 1971-74 bed erosion on MLTC and SOBR amounts to 192 t.

## SEDIMENT YIELD AND DISSOLVED LOAD

### Suspended Load

Suspended-sediment concentrations measured in Lone Tree Creek range from 1 to 16 000 mg/liter. Concentrations during storms are typically 200 to 1000 mg/liter; after storms they drop rapidly to 10 to 30 mg/liter or less. Silt and clay make up over 50 percent of the sample, even at the highest sediment concentrations. Sediment concentration is controlled chiefly by rate of supply from extrachannel erosional processes, particularly sheet erosion in slide scars and on gully walls, bank spalling and caving, and slides and debris flows (Lehre 1981). Total suspended load discharge from the drainage basin during 1971-74 was 3157 t, or 607 t/km$^2$ per year (table 3).

### Bedload

Where sediment is present, the bed of Lone Tree Creek is gravel or boulders; mean bed-particle diameter ($d_{65}$) ranges from 28 to 142 mm in reaches near the gaging sites. By contrast, mean diameter ($d_{65}$) of material in my bedload-transport samples ranged from 3.5 to 18 mm, and 25 to 70 percent by weight consisted of particles less than 4 mm. This fine material has two sources: part of it resides in the bed beneath a surface armor layer; the remainder is directly contributed to the flow by slides, gullies, and bank erosion. Measured unit-transport rates are about 0.01 to 0.10 kg/second per meter of channel width.

Bedload discharge was computed from a rating curve which, though defined by only five points, yields estimates of $Q_b$ at high discharge (more than 4 m$^3$/second) that are only 15 percent lower than those predicted by the Meyer-Peter and Müller (MPM) equation (Vanoni 1975). At lower flows, the equation overestimated bedload transport by 3.5 to 15 times.

Total bedload discharge for the period 1971-74 was 422 t (85 t/km$^2$ per year), or about 14 percent of the suspended-load discharge (table 3). I believe the bedload estimates are within ± 50 percent of the true bedload discharge.

### Dissolved Load

The most distant part of the Lone Tree drainage basin is less than 2.4 km from the ocean, suggesting that "cyclic salts" (Janda 1971) carried inland by wind and rain may be an important constituent of the dissolved load. Janda (1971, table 2) found that nondenudation components accounted for 55 percent of total dissolved load in two coastal streams in San Mateo County. I also obtained a value of 55 percent for nondenudation components in a water sample from Pike County Gulch, a small coastal drainage basin similar to Lone Tree Creek, but 8 km north. I assume this percentage applies to the Lone Tree drainage basin as well. For the period 1971-74, I computed a total denudation dissolved load of 196 t (37.5 t/km$^2$ per year), or about 6 percent of total denudation in the drainage basin (table 3).

Table 4--Sediment mobilization on slopes, production to channels, and yield (discharge) from drainage basin for years 1971-74 on Lone Tree Creek. See text for discussion.

| Year | Rainfall | Recurrence interval of peak flow | Mobilization on slopes (1) | Production to channels (2) | Redistribution on slopes (3) | Yield: bed + susp. load (4) | bed + bank storage (5 = 2 - 4) |
|---|---|---|---|---|---|---|---|
| | Millimeters | Years | Metric tons km$^2$ | | | | |
| 1971-72 | 602 | 1.5 | 86 | 148 | -71 | 24 | +124 |
| 1972-73 | 1184 | 15-20 | 1219 | 985 | +317 | 1420 | -435 |
| 1973-74 | 1046 | 3-5 | 1960 | 1575 | +389 | 630 | +945 |
| 1971-74 | 2832 | -- | 3265 | 2708 | +635 | 2074 | +634 |

### Long-Term Estimates

"Long-term" estimates of suspended-sediment, bedload, and dissolved-solids yields (table 3) were computed by using their average 1971-74 rating curves in conjunction with an "average" duration curve synthesized from a dimensionless regional flow-duration curve for Marin County streams (Lehre 1974, fig. 12; Lehre 1981). These estimates assume that the present period is representative of past conditions. If landslide frequency has increased in the last 100 to 150 years (see discussion), this assumption is invalid.

## SEDIMENT BUDGET

### Reconciliation

The third and final step in construction of a sediment budget is setting up a balance sheet showing mobilization, production, sediment yield, and storage changes. I have done this in table 4, using the data in tables 2 and 3.

Table 4 represents a simplification of the relations shown in figure 2. Storage elements are lumped simply into hillslope and bed-and-bank sites; available data are insufficient for finer discrimination, especially in the channel component. Processes included in mobilization on slopes are those listed in the upper (hillslope) half of figure 2. Production to channels includes all material mobilized by the processes listed in the lower (bed and bank) half of figure 2, together with all material mobilized by hillslope processes that reached or had access to a channel. This estimate of production assumes that all material mobilized by scarp and sheet erosion in slide scars connected to the channel system is delivered to the channels. In fact, some unknown proportion of this sediment remains behind in the scar.

In calculating production, creep and hillslope sheet erosion are not explicitly included. Material moving downslope by these processes enters the channel system through bank and gully-wall erosion and is accounted for there (table 2).

Redistribution on slopes is the difference between the total amount of sediment mobilized by slope processes and that produced. This represents the amount of material moved from one position of hillslope storage to another farther downslope. Negative values indicate transfer of sediment to bed and bank storage exceeds new mobilization on hillslopes. This implies growth of gullies and scars at the expense of the slope.

The difference between production to channels and sediment yield (transport out of drainage basin) gives the change in bed and bank storage. Negative values of this quantity indicate that removal of material from bed and bank storage exceeds resupply from hillslope processes. Positive values represent new accretions to storage (from slopes above) and possibly redistribution of material already in bed and bank storage.

### Discussion

The sediment budget of table 4 demonstrates convincingly that in dry years and in wet years without extreme flow events most of the sediment mobilized goes into storage, chiefly on the lower parts of slopes and in channel and gully beds and banks. Large net removal of sediment from storage occurs in flow events with recurrence intervals greater than 10 to 15 years. Process measurements suggest a reason for this. In an "average" or a dry year, gully-wall erosion and slide-scarp retreat are the chief mobilizers of sediment (table 2). Most of this material is moved by spalling, local sliding, or rainbeat, and is not transported far before being deposited and returned to storage. Only sheet erosion in slide scars and, to a lesser extent, on gully walls and gully headcut retreat can effectively entrain and remove sediment; these are, in fact, the main sources of suspended load in such years. By contrast, in years with extreme rainfall and flow events (such as 1973), debris slides and flows are responsible for over 80 percent of all sediment mobilized and between 55 and 65 percent of all sediment produced. In these years, gully-wall, bank, and bed erosion are also much increased. Because nearly all of this material is contributed directly to the channel during very high flow, when the stream has the capacity to transport it, most of it is carried out of the drainage basin.

The importance of very large flows in preventing sediment from re-entering storage can be seen by comparing 1973 and 1974. In 1973, a year with a 15- to 20-year flow event, about 1550 t were contributed to channels by slope processes (55 percent from debris flows) and measured bank erosion, yet 2465 t were discharged from the drainage basin. The difference must have come from unmeasured bed and bank erosion. In 1974, a year with only a 3- to 5-year flow event, about 2720 t were contributed to channels, 78 percent came from two large landslides prepared for failure by undercutting the previous year. Only 1090 t were discharged from the drainage basin, however, primarily because the peak flows were insufficient to transport the amounts of sediment supplied (Lehre 1981).

Ideally, a sediment budget should specify the magnitude and frequency (recurrence interval) of sediment mobilization by each process and the average residence time of sediment in each storage element. These are difficult questions; their general answer requires both longer records of process activity, and better quantitative models of relations between process activity and driving forces and of movement of sediment through storage elements, than are currently available. My data do, however, provide insights into some of the problems of process relations and residence time in swales.

Debris slides and flows are the single most important erosional agent in the drainage basin, accounting for at least 53 percent (112 $t/km^2$ per year) of its "long-term" particulate yield (214 $t/km^2$ per year). The magnitude and frequency of sliding are thus clearly important to understanding sediment routing in the drainage basin, but their determination is a vexing and yet unsolved problem.

Recurrence intervals of rainfall events (or, as a surrogate, flow events) and sliding are not simply related for four reasons. First, extreme events in 1 year (e.g., 1973) may undermine or weaken slopes so that they fail in subsequent smaller events (e.g., 1974). This destroys the independence of events commonly assumed in recurrence interval calculations. Second, a particularly large rainfall event may evacuate a large proportion of the sediment in storage in swales, thus reducing the amount of sediment available for mobilization in subsequent large storms. Third, as the colluvial fill in a swale accumulates, thickens, and weathers, its probability of failure in a storm of a given size increases. The volume of slides produced by a storm of specified frequency will thus depend not only on storm magnitude, but also on the filling history of the swales. Finally, changes in drainage-basin vegetation from fire, storm, land use, or natural succession may markedly alter the susceptibility of slopes to failure, and thus change magnitude-frequency relations. Until these problems can be adequately dealt with, landslide "recurrence intervals" will not be particularly meaningful.

Slide scars fill through creep and scarp erosion. Creep and hillslope sheet erosion supply sediment to slide scarps at a maximum rate of 0.0009 $m^3/m$ per year; scarps, however, are eroding at 0.0054 $m^3/m$ per year and thus must be wearing back at the expense of the slope. Assuming then that scars fill primarily by scarp erosion, that all sediment so mobilized remains within the scar, and that the linear rate of scarp retreat is constant (20 mm/year), simple calculations (Lehre 1981) suggest a minimum of 540 years are required to fill a 2.5 m deep scar to half its depth. Reasonable changes in assumptions increase healing time by a factor of 5 to 10.

Continued maintenance of colluvial fills in swales demands that long-term rates of filling by creep and emptying by slides be in equilibrium. Density of swales is $129/km^2$; assuming a "typical" swale length of 60 m and a 0.6-m-thick moving mantle, a creep rate of 13 mm/year is required to maintain equilibrium with the "long-term" slide rate of 187 $t/km^2$ per year (Lehre 1981). Observed creep rates are 0.75 to 1.5 mm/year over a depth of 0.4 m, suggesting colluvium is currently being stripped. For the colluvial fills to have accumulated, then, past creep rates were either 10 times higher than at present, or rates of landslide erosion were 10 times lower. This hypothesis will be more rigorously tested as additional slide and creep data are collected.

Under the assumption, used to calculate the long-term slide rate, that all raw and recovering slides are less than 100 years old, the frequency of slide occurrence in the past century is 226/100 years. Assuming that all 94 healed slides are between 100 and 540 years old, their frequency of occurrence is about 21/100 years, suggesting a tenfold increase in slide frequency in the past century. (Note that increasing the age of the oldest recognizable healed slide, or decreasing the age of the oldest raw/recovering slide, only increases the disparity in rates. To have about equal frequencies, the raw and recovering slides would have to have ages of 0 to 250 years, and healed scars would be 250 to 350 years old. These ranges do not seem realistic, particularly for healed slides, which may actually range in age from less than 100 to more than 550 years.)

Taken together, creep rates and slide numbers strongly suggest that landslide frequency has increased tenfold in the past 50 to 150 years, and that sliding is currently mining relict colluvium formed in equilibrium with creep rates about equal to current creep rates. The timing of this increase corresponds closely with the introduction of cattle to the drainage basin, and the resultant conversion of the grasslands from the longer rooted, perennial, native bunch grasses to shallower rooted, annual, introduced grasses. This, combined with trampling and heavy grazing, may have been sufficient to weaken slopes already near the limits of stability.

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# Plant Growth and Block-Field Movement in Virginia

Cliff R. Hupp and Robert S. Sigafoos

## ABSTRACT

Tree-ring dating provides information on temporal and spatial aspects of related geomorphic processes. Studies in Massanutten Mountains in Virginia involve effects of mass movement on trees and how these effects can be used to date movement of block fields. Block fields occur below resistant Massanutten sandstone in Passage Creek basin. Slopes are boulder-strewn, and locally vegetation is absent or sparse. Trunk ages yield a minimum age for a geomorphic/hydrologic event. Corrasion scars yield exact year of occurrence. Dates correlate with extreme flows on Passage Creek. Pleistocene frost action may have facilitated original formation of block fields, but some now spread during intense rainfall, though climatic conditions are different from those at formation.

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Cliff R. Hupp and Robert S. Sigafoos, Botanists,
U.S. Geological Survey, Reston, Virginia 22070.

## INTRODUCTION

Dendrochronologic methods have had wide use in dating occurrence and determining rates of both hillslope and fluvial geomorphic events and processes. These methods are a valuable tool in quantifying some erosion processes and sites of sediment storage in forested areas. Most work of this type has occurred where geomorphic activity is conspicuous. Here, we examine the character of more subtle geomorphic processes, which can locally provide a source of coarse particles for streambed armouring and influence bedload characteristics downstream of block-field areas.

The block fields were identified in the field and on aerial photographs. The primary site is in the northern part of the Massanutten Mountain Range near Passage Creek in northwestern Virginia (fig. 1). The range is a syncline underlain by resistant Massanutten sandstone consisting of white quartz sandstone and quartzite, locally conglomeratic. The Martinsburg shale formation occurs immediately below, and many block fields have formed at this contact (Rader and Biggs 1976). They have slopes between 32 and 42 degrees, with boulders ranging from several centimeters to a few meters in diameter (fig. 2). The slopes are a mosaic of block fields and forested patches; the predominant forest species are chestnut oak (*Quercus prinus* L.), cherry (*Prunus serotina* Ehrhart), black gum (*Nyssa sylvatica* Marshall), birch (*Betula lenta* L.), American ash (*Fraxinus americana* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), American basswood (*Tilia americana* L.), and black locust (*Robinia pseudoacacia* L.). Common subcanopy species are dogwood (*Cornus florida* L.), shadbush (*Amelanchier arborea* Fernald), ironwood (*Carpinus caroliniana* Walter), witch hazel (*Hamamelis virginiana* L.), and pawpaw (*Asimina triloba* (L.) Dunal). Taxonomy follows Radford et al. (1968).

Trees growing on, near, or below the block field provide evidence of recent movement. Movement can be dated through tree-ring analysis of leaning trees with adventitious sprouts, stem deformations, and corrasion scars. Tree ages on new deposits provide a minimum time since deposition, and tree ages above the block field but below the outcrop indicate the minimum time since relative stability was reached.

Some geologists believe that block fields or scree in the central Appalachians are Pleistocene relicts and not now subject to frequent movement (Hack, J. T., U.S. Geological Survey, Reston, Virginia, personal communication). Block fields occur downslope from resistant sandstone outcrops from which individual blocks were probably first formed by frost action during the Pleistocene. The block field studied is currently spreading downslope, and the time of movement correlates with recorded floods.

Block fields are a common feature of the Massanuttens. Although some appear to be stable, most have vegetative indications of movement. Analyzing the process by which the block fields move poses many problems; however, our study suggests moving water is a prime factor.

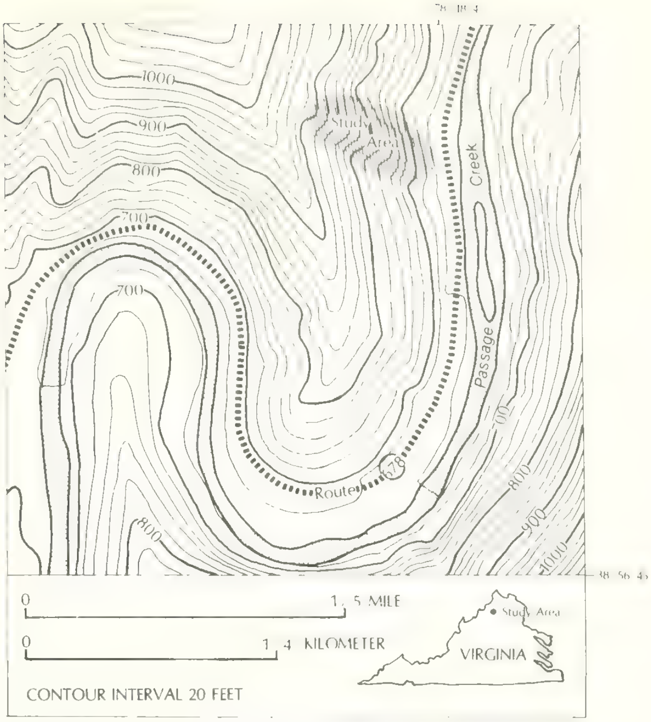


Figure 1.--Part of the Massanutten Mountains, Virginia, showing study area.

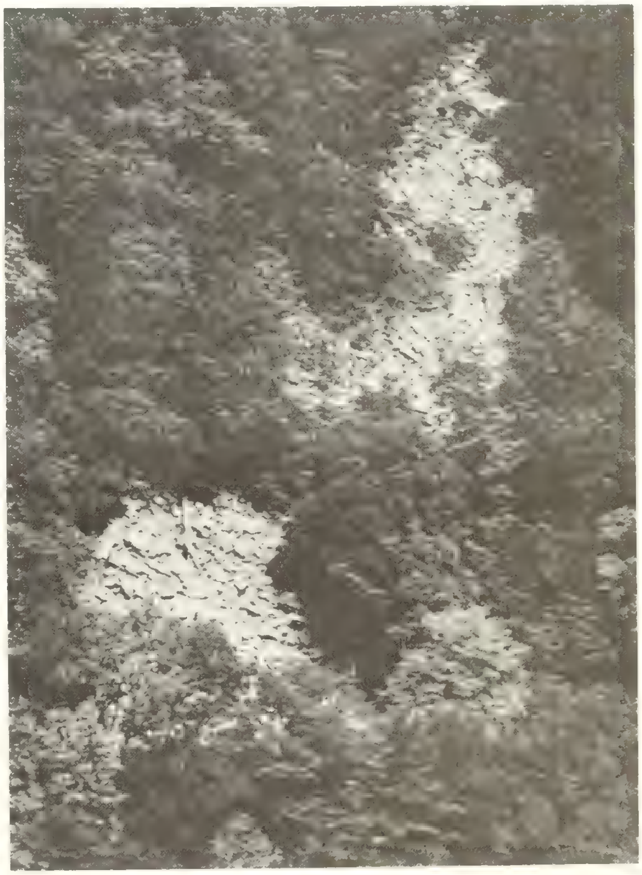


Figure 2.--The block field studied. Visible part of fallen log is 6 m long.

## METHODS

### General Principles

The basic principles of tree-ring dating have been outlined extensively (Sigafoos 1964, LaMarche 1968, Alestalo 1971, Sigafoos and Hendricks 1972, Shroder 1978). Slope movement and rockfall can have many effects on woody vegetation, including partly felling trees, scarring stems, and creating bare areas where plants can become established. Tree-ring analysis allows for fairly rapid and reliable dating of recent geomorphic activity (Alestalo 1971). The ability of individual trees to recover from damage and still record the event in their annual-ring chronology provides a valuable research tool for geomorphic studies. Use of dendrochronology in dating geomorphic phenomena should shed light on some incompletely understood processes.

Tree trunks grow radially during spring and early summer. Wood formed in spring is different from wood formed the previous summer. This difference produces an annual ring, so each year's growth can be identified and dated. Some species have ring morphologies that allow for ease of measurement. These trees are "ring porous"; that is, the wood that forms in the spring has large pores that form a conspicuous ring when viewed in cross section. Others are "diffuse porous," with uniform pores throughout the annual ring. In dating geomorphic events, one does not have the luxury of picking select species and individuals. Land-use history, age of stand, life history of the species, and diffuse-porous species all pose problems. On the slopes we studied, two common species (birch and black gum) exhibit the effects of mass movement in their deformations, but because both are diffuse porous, the annual-growth increments are difficult to see. Some species also have extra or missing rings. Considerably more care has to be exercised in ring-boundary determinations and ring counts than would be necessary if we could use only selected species (Phipps, R. L., U.S. Geological Survey, Reston, Virginia, personal communication).

Eccentric annual growth can be seen in stem wood where one side of the trunk produces more wood than another. Should this occur for several years, the center of the section or core appears to be skewed to one side of the trunk, or in other words, radii in opposite directions will be unequal in length. Eccentric growth can result from an unequal direction of incident light (a phototropic response) or tilting (a geotropic response). Determination of onset, magnitude, and duration of eccentric growth can indicate the date, direction, and duration of a geomorphic event. The cause of the eccentric growth must be ascertained, however, before this technique is reliable (Phipps 1974). Angiosperms--deciduous, broad-leaved flowering plants--produce thicker annual rings on the uphill side; gymnosperms--coniferous plants--produce thicker rings on the downhill side. Reaction-wood formation producing eccentric rings is often difficult to analyze in angiosperms.

Severe tilting can cause adventitious sprouting along the parent trunk, and such sprouting is common in angiosperms. Sprouts from trunks of tilted trees are found often around block fields and along stream courses. Because sprouting occurs rapidly after a geomorphic or flood event, the age of the sprout will date that event to the year (Sigafoos 1964).

The corrasion of tree stems by rockfall damages the cambium (wood-producing region). This can result in termination of radial growth where the tree was struck. In subsequent years, the scar will be increasingly covered by callus growth until the damaged area is completely covered and the cambium is once again continuous around the trunk (fig. 3). Cross sections through the scarred portion of a trunk can yield the exact year of damage and often the season. LaMarche (1968) and Shroder (1978) have used this technique to date active slope movement. Increment cores taken at different angles on either side of a scar make dating possible without destroying the tree (fig. 4).

Increment cores taken at the base of a tree growing on a landform can yield the minimum time lapsed since the landform assumed some measure of stability. Sigafoos and Hendricks (1961, 1972) used this technique extensively in dating glacial deposits. Serial age determination of trees downslope on a block field from head to leading edge may yield an approximate rate of downslope movement. We are currently testing this procedure.

### Methods Used

All of the techniques outlined in the preceding paragraphs were employed on the studied block-field slope. Figure 5 illustrates samples of three major tree-ring techniques used in this study.

Increment cores for age determination were taken from 39 sprouts growing from inclined trunks (fig. 6). Cross sections or cores from 55 tree stems were taken to date scars, and 48 core samples were taken to date the age of the landform surface. These data were then compared to existing streamflow records obtained from the Virginia Water Control Board for the period 1933-78. Dates of high flow were determined and used to ascertain possible correlations of block-field movement.

Field observations of lichen coverage and degree of weathering of the rock were made. Although variations in these characteristics of block fields can support tree-ring dating techniques, we believe they cannot date movement as accurately. In this study, they were used as supportive evidence of movement.

A map of the block field was drawn from aerial and oblique ground photographs and from field measurements with a compass and range finder. Areas of movement on the block field were identified by absence of lichen cover and unweathered surfaces of rock, and movements were dated using the trees below or near the movement.

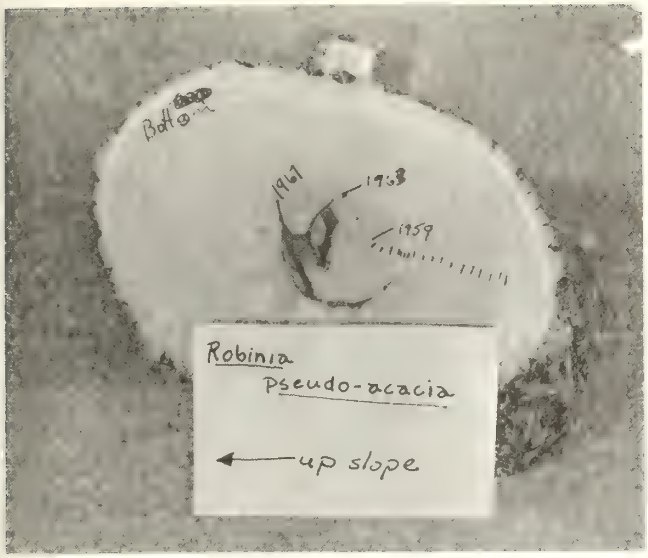


Figure 3.--Multiple scarring and annual callus growth in black locust.

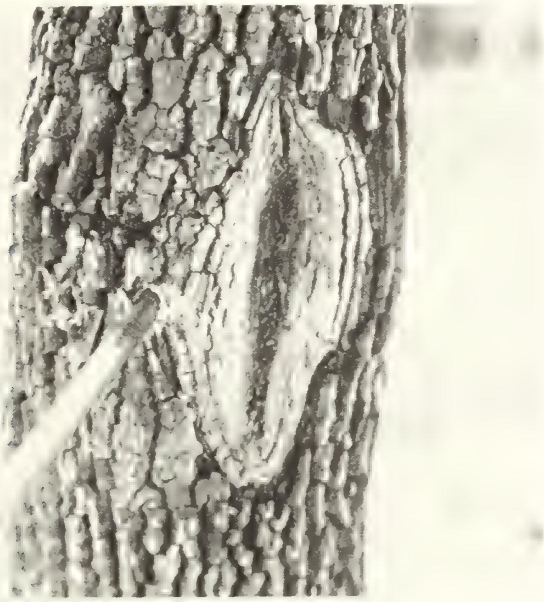


Figure 4.--Growth of callus wood indicates older scar on chestnut oak. Core samples from just outside calus can date the scar.

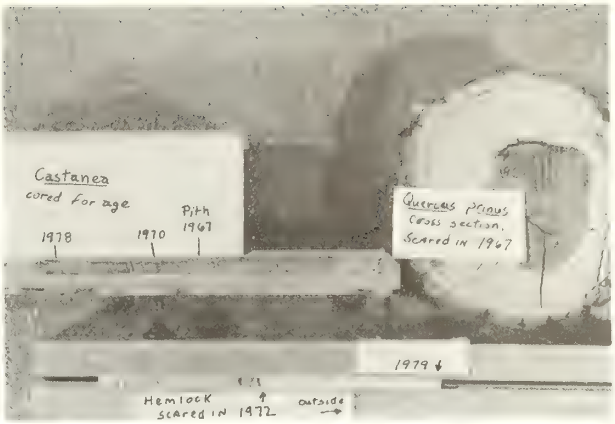


Figure 5.--Examples of three types of information obtained by tree-ring analysis. Tree ages may be determined from increment cores (upper left: chestnut sprout from a parent damaged by a rock fall). Damage date may be determined from increment cores (bottom: hemlock, cored to date scar formation, 1972) and from cross sections (upper right: chestnut oak, sectioned to date scar, 1967).

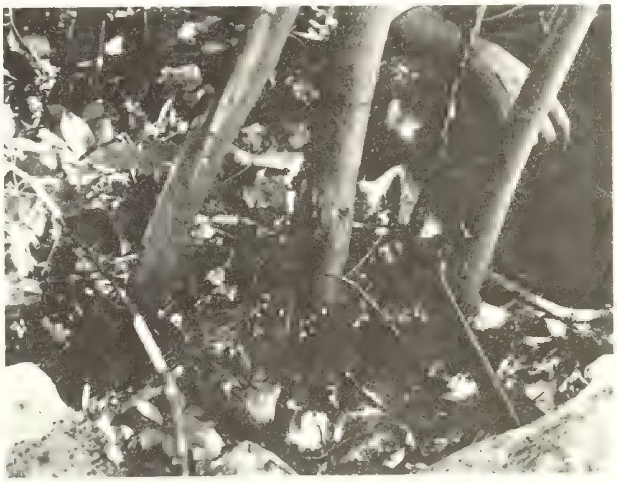


Figure 6.--Adventitious sprouts from severely tilted parent. Age of the sprouts can indicate time since tilting. Note core hole in center sprout.

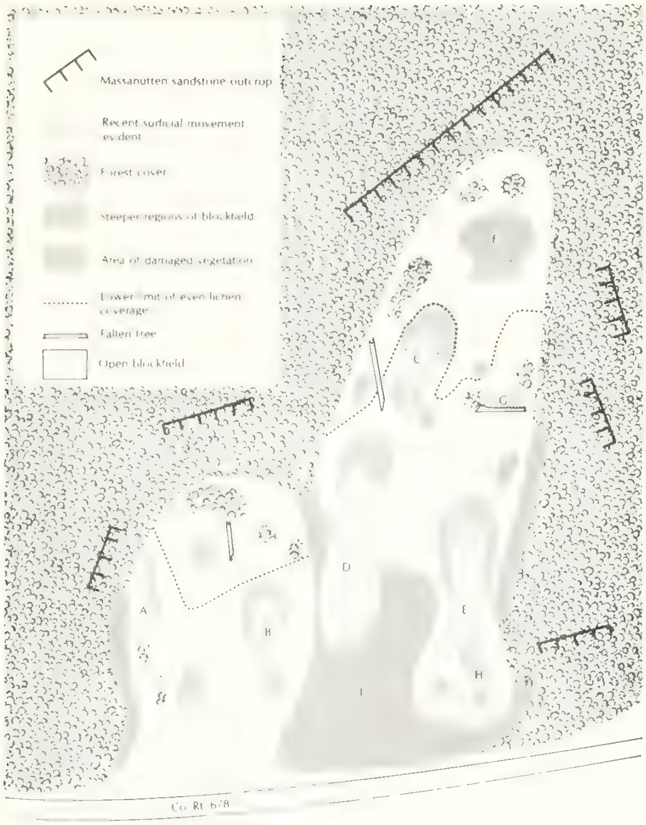

Massanutten sandstone outcrop
Recent surficial movement evident
Forest cover
Steeper regions of blockfield
Area of damaged vegetation
Lower limit of even lichen coverage
Fallen tree
Open blockfield
A
B
C
D
E
F
G
H
I
Co Rt 678

Figure 7.--Map of block field:

A. and B. Depression in block field with unweathered smaller boulders. A. has tree-ring evidence of movement in 1979 and 1972.
C. Recent slope failure. Tree-rings date movement in 1967.
D. Recent slope failure. Tree-rings date movement in 1967, 1972, and 1979.
E. Recent slope failure. Tree-rings date movement in 1942, 1954, 1967, 1972, and 1979. Smaller boulders at lowest portion may move with every substantial rain event.
F. Pawpaws growing in block field. Scars on stem below surface do not correspond to flood events.
G. Fallen tree damming debris upslope, with depression downslope.
H. Severely damaged vegetation. Boulders subject to frequent movement during most rain events.
I. Scattered boulders among vegetation with extensive tree damage.

## RESULTS

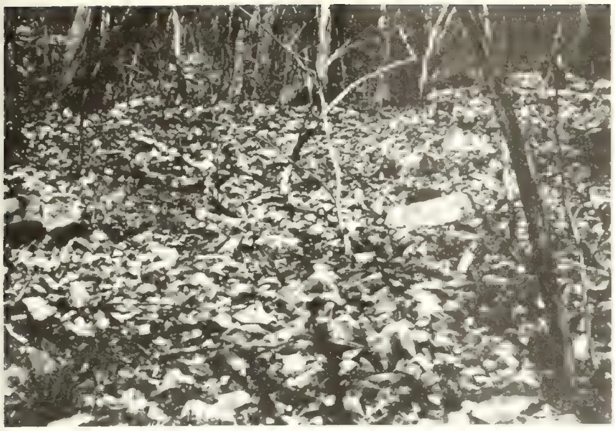
The map of the block field (fig. 7) shows where recent movement was indicated by either vegetation or fresh rock exposure. Boulders in the most active lower portion are considerably smaller than those upslope, ranging from 10 to 25 cm in diameter, with a few larger. In depressions of recent slope failures (C and D, fig. 7), boulders ranged from 20 to 35 cm in diameter. In the relatively stable upper portions of the block field (area of even lichen coverage, fig. 7), the boulders are generally greater than 35 cm. Throughout the block field, isolated very large (up to 3-m) boulders are found. In the depressions and the lowest part of the block field, boulders are found with lichens on the underside and recently exposed upper surfaces.

A fallen log (G, fig. 7) created a debris dam. Downslope from the log, material has been removed, producing a depression in the surface material, while debris was piled against the upslope side of the log. LaMarch (1968, p. 372-373) has used this type of evidence to document movement. An attempt was made to cross-date the log with living vegetation so that time in that position could be ascertained. Fallen timber in the East is not preserved well; a minimum time since death was determined by ring counting to be 25 years, but whether the tree fell the same year it died is not known. The methods of cross-dating are described by LaMarche (1968, p. 351).

One of the 18 pawpaws (F, fig. 7) was excavated to 1.5 m and was visible for another half meter into the block field. All of the excavated portion of the trunk was stemwood, indicating that the point of germination was deeper in the block field. A corrasion scar at 30 cm below the block-field surface indicates internal movement. The surface boulders near the pawpaws were loose but had even lichen coverage, suggesting no recent, rapid, surficial downslope movement.

The trees between the block field and the outcrop ranged from 176 years old to seedlings. Trees are oldest near the outcrop and are progressively younger toward the block field. The age distribution from outcrop to block field indicates that the forest is becoming established in the stable upper part of the block field. The vegetated area below the block field has young trees (fig. 8) of ages that correlate with periods of little tree deformation and no major floods. Many trees are dead or in poor condition, presumably as a result of corrasion from numerous rock falls. Boulders are scattered on the forest floor, commonly lodged on the upslope side of a tree trunk (fig. 9).

Of 152 trees analyzed on this block field, growth of 94 correlated with major floods on Passage Creek (fig. 10, table 1). Not all tree-ring evidence correlated with floods on Passage Creek. Many trees predated the existing flood record or did not indicate a particular year with enough trees damaged to be considered significant (greater than three).



igure 8.--General view of lower lobe of block ield.

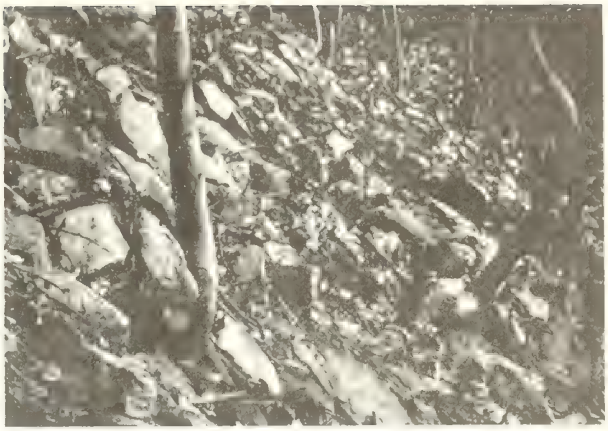


Figure 9.--Active lower part of block field. Small trees here exhibit many stem deformations and eccentric growth.

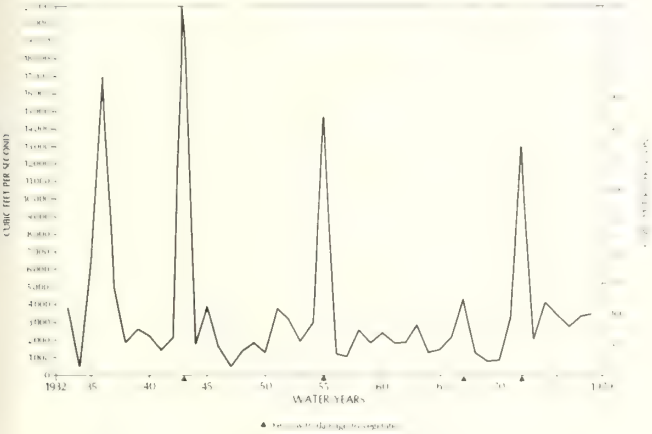


Figure 10.--Annual peak discharges. Passage Creek near Buckton, Virginia (1933-78). A water year is from October 1 through September 30. A flood in October of 1942 would be in water year 1943.

Table 1--Numbers and type of tree-ring evidences corresponding to floods on Passage Creek; of the 58 in nonflood years, 39 predated existing flood record

| | Floods on Passage Creek | | | | | |
|---|---|---|---|---|---|---|
| Evidence | 1979 | 1972 | 1967 | 1954 | 1942 | Nonflood years |
| Corrasion scars | 20 | 9 | 19 | 4 | 1 | 12 |
| Sprouts from tilting | 0 | 5 | 10 | 5 | 2 | 17 |
| Age of main stems | 0 | 4 | 4 | 7 | 4 | 29 |
| Total | 20 | 18 | 33 | 16 | 7 | 58 |

## CONCLUSIONS AND DISCUSSION

Our research has demonstrated that some block fields are currently spreading downslope. This movement can be recorded on the trees growing near the block fields, and dates of recent activity can be determined by tree-ring analysis. The correlation of dates of movement with high streamflow suggests that high precipitation is a prime factor in current block-field activity.

### Botanical Evidence

Analysis of corrasion scars is the most accurate method of dating block movement. The trees, however, in a relatively short time can obscure outward evidence of corrasion. The method is thus limited to dating more recent events (note the general decline in importance of corrasion scars with age in table 1). Undoubtedly, if older trees were cross sectioned, a longer scar chronology could be developed, but this would kill the trees. Adventitious sprouting from tilted trees (fig. 6) occurs within 1 year after tilting; this sprouting is therefore accurate to within 1 year and is generally easy to identify. Assurance that the tilting is a result of slope failure cannot be made as easily as corrasion is analyzed. Age of trees growing on degraded or aggraded areas can be determined as long as coring is done at the base of the tree. Dating the geomorphic event in this manner yields an estimate rather than an exact date because time to seedling establishment after an event is variable (Sigafoos and Hendricks 1961). Dating older events by tree ages is limited by the life span of the tree species (note the increase in importance of tree age as a dating technique with time in table 1).

Absence of lichens on a block's surface was used in this study to pinpoint areas of recent slope failure, and regions of the block field with even lichen coverage were interpreted as stable or moving slowly as a unit. Lichenometric techniques have not been used in the Massanuttens to date block-field surfaces. Until lichen growth rates are established in this region, reliable estimates cannot be made. The climate in Virginia, compared to colder regions, may increase the rate and variability of lichen growth, and the action of herbivores on the lichen thallus may also be increased. These factos may reduce the reliability of lichenometric dating at this site (Lawry, J. D., Biology Department, George Mason University, Fairfax, Virginia, personal communication).

### Movement Mechanism

Block fields in the Massanuttens may have formed as talus below sandstone outcrops or have accumulated above the rock from which they were derived (Hack 1965, p. 32). Traditionally, the block fields have been considered stable relicts of Pleistocene climate, where frost action facilitated their formation.

Our research and that of Hack (1965, p. 32-44) indicate that some block fields are still actively moving downslope. Block fields below outcrops are locally many meters downslope from the outcrop. A reasonable speculation is that separation of the block field from the outcrop indicates a cessation or slowing of frost action on the outcrop, while the increased rainfall of Holocene climate has moved the bulk of the block field downslope from the outcrop. Without the continued supply of material from the outcrop, active block-field slopes may be considered out of equilibrium.

A possible mechanism for current movement would be the buildup of a hydrostatic head within the block field during intense rainfall. Given sufficient slope angle and hydrostatic pressure, parts of the lower end may blow out, producing small debris avalanches or lobes. The more stable upper reaches then shift downward, much less dramatically, adjusting to the removal of material downslope (fig. 11). Eisenlohr (1952) has described "blowouts" of this nature in Pennsylvania. The block field rests on relatively impermeable shale, which would concentrate runoff deeper and lower in the block fields, causing water to accumulate at the base of the block field. The presence of pawpaws, which grow in wet areas, on a south-facing (usually dry) slope such as the studied block field, indicates wetter conditions that would be expected.

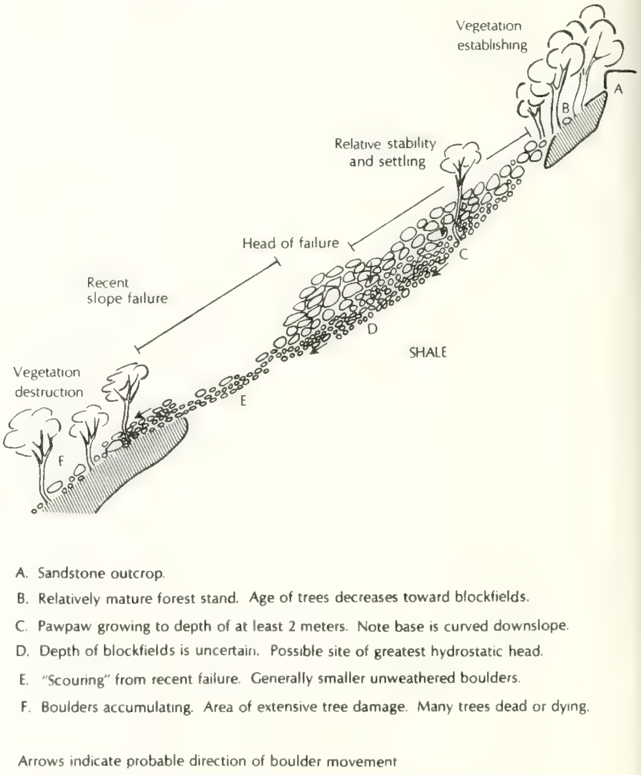

Vegetation establishing
A
B
Relative stability and settling
Head of failure
C
Recent slope failure
D
SHALE
Vegetation destruction
E
F
A. Sandstone outcrop.
B. Relatively mature forest stand. Age of trees decreases toward blockfields.
C. Pawpaw growing to depth of at least 2 meters. Note base is curved downslope.
D. Depth of blockfields is uncertain. Possible site of greatest hydrostatic head.
E. "Scouring" from recent failure. Generally smaller unweathered boulders.
F. Boulders accumulating. Area of extensive tree damage. Many trees dead or dying.
Arrows indicate probable direction of boulder movement

Figure 11.--Cross section of block field:
A. Sandstone outcrop.
B. Relatively mature forest stand. Age of trees decreases toward block fields.
C. Pawpaw growing to depth of at least 2 m. Note base is curved downslope.
D. Depth of block fields is uncertain. Possible site of greatest hydrostatic head.
E. "Scouring" from recent failure. Generally smaller unweathered boulders.
F. Boulders accumulating. Area of extensive tree damage. Many trees dead or dying. Arrows indicate probable direction of boulder movement.

The lack of fine material in the block fields has caused some problems with the idea that a hydrostatic head is created during intense rainfall. J. T. Hack (U.S. Geological Survey, Reston, Virginia, personal communication) believes, as we do, that hydrostatic pressure during intense rainfall is enough to create a blowout, considering the slopes have an angle of 32 to 42 degrees. Smaller blocks, pebbles, and sand are commonly found in or below the most recent blowouts.

Ice lenses in the pore spaces may block runoff, thus increasing the hydrostatic pressure. This process, however, would be most effective during colder seasons. More research is needed before the season of greatest block-field movement can be determined. We have dated movement during October 1942, probably caused by a severe flood. Movement during 1967 correlates with a flood in March, and fresh corrasion scars on trees were found in March of 1979. Corrasion scars older than the flood record indicate damage just prior to early wood formation which suggests winter or early spring activity.

Slope failure from intense storms is common in the Appalachians, often with devastating effects. We believe that the correlation between tree-ring dates of block-field activity and flood records is more than coincidence. Some lack of correlation could result from intense local convectional storms over a block-field area which may not produce general flooding on Passage Creek.

The periodic mass movement of block fields in the Massanuttens may represent a major means of downwasting in these highly resistant areas. The block fields investigated are responding to current climatic conditions different from those at the time of formation (Hack and Goodlett 1960, p. 62-63). Block fields, at least those studied, are an active part of today's landscape, rather than a relict of the Pleistocene.

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# Hillslope Evolution and Sediment Movement in a Forested Headwater Basin, Van Duzen River, North Coastal California

Harvey M. Kelsey

## ABSTRACT

The study was made on the 160-km$^2$ headwater basin of the Van Duzen River. Erosion in steep, forested first-order drainage basins is mainly by debris avalanches, any one of which can encompass a large proportion of the drainage-basin area. After initial deposition of debris in the headwater channel, the rate of subsequent downstream sediment movement depends on the sites of deposition, the occurrence of major climatic events that generate more debris avalanching, and the recovery times of hillslopes affected by avalanching. Residence time of debris on headwater slopes ranges from 15,000 to 50,000 years. Once debris enters perennial stream courses (first-order through third-order streams), sediment transit time out of the study area ranges from less than 10 years to about 5,000 years, depending on whether sediment is temporarily stored in the active channel, in thick channel fills, on strath surfaces isolated by downcutting, or on wide alluviated valley bottoms.

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Harvey M. Kelsey, Geologist, National Park Service, Redwood National Park, Arcata, California 95521.

## NTRODUCTION

he purpose of this paper is to discuss sediment movement in the uppermost portion of a steep, orested drainage basin in the Coast Ranges of northern California. The study area is the 160-km$^2$ upper drainage basin of the 1111 km$^2$ an Duzen River basin (fig. 1). The Van Duzen is he northernmost tributary of the Eel River; it lows into the Eel 22 km upstream of its mouth 180 km north of San Francisco.

The Van Duzen and other California north coast rivers have the highest sediment yield of basins of comparable size in the United States (Judson and Ritter 1964, Brown and Ritter 1971). In other papers (Kelsey 1977, 1978, 1980), I have discussed in detail the major geomorphic processes that operate in the Van Duzen River and I have presented a quantified sediment budget for the Van Duzen above the U.S. Geological Survey gaging station that covers the upper 575 km$^2$ of the drainage basin. Neither the measured sediment yield at the gaging station nor the sediment budget for the basin, however, adequately describes in detail the processes of erosion and deposition in any one part of the drainage basin. This paper describes hillslope erosion, sediment movement in channels, and landscape evolution in the uppermost part of the Van Duzen. The small drainage area and fairly homogeneous bedrock create a nearly ideal study site that is not complicated by many geomorphic processes and numerous landform types.

## GEOLOGIC AND CLIMATIC SETTING

The Van Duzen drainage basin drains rocks of the Franciscan assemblage (Bailey et al. 1964), which is a Mesozoic to early Cenozoic accumulation of folded, sheared, and faulted continental margin deposits. Geologic mapping (Kelsey and Allwardt 1975) shows both melange and sandstone units occur in the lower two-thirds of the drainage basin, but in the upper basin study area the principal rock types are slightly metamorphosed, competent graywacke sandstones or interbedded sandstones and siltstones. Although I will not discuss the lower drainage basin in this paper, the presence there of Franciscan melange as well as Franciscan sandstone is a notable distinction from the study area. Franciscan melange hillslopes range in morphology from smooth, undulating grassland or grass-oak woodland slopes to hummocky, boulder-strewn, poorly drained grasslands sculpted by creep or earthflow landslides. Forested sandstone and siltstone slopes of the study area, by contrast, are smooth and straight (fig. 2). The highly sheared and faulted character of these Franciscan rocks, in combination with their present tectonic setting and regional climate, are the cause of the high rates of erosion.

Distinctive landforms testify to recent tectonic uplift of the area. These landforms include narrow, deeply cut river canyons incised below more moderately dipping upper slopes; abundant young strath terrace surfaces elevated above the major rivers; and actively downward and headward cutting steep, headwater channels.

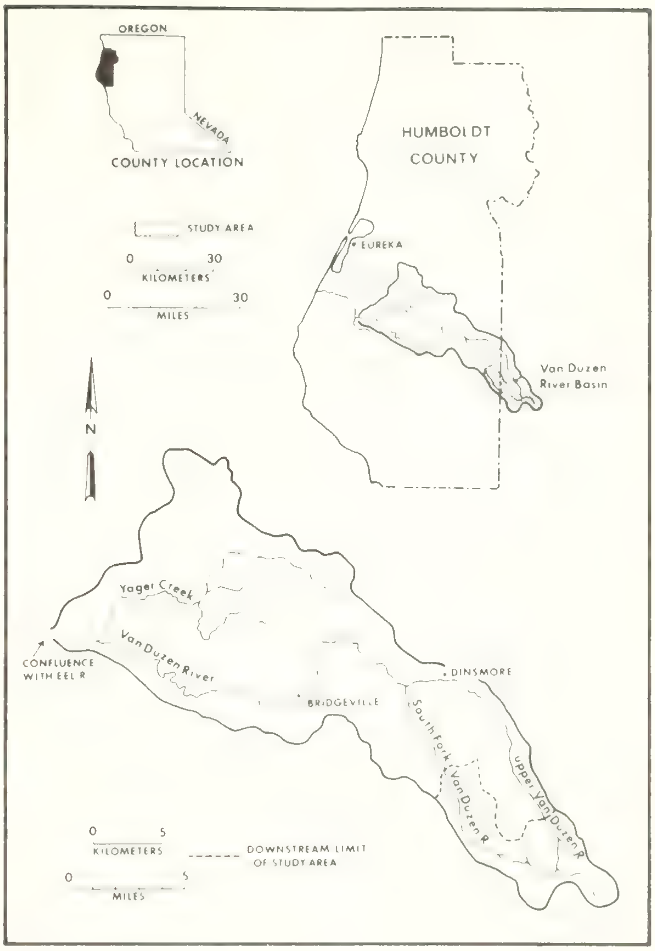


Figure 1.--The 1111-km$^2$ Van Duzen basin, showing the 160-km$^2$ study area in the upper portion of the basin.

Figure 2.--The steep, forested study area in the headwaters of the South Fork Van Duzen drainage basin (right). Typical melange terrain, vegetated with grassland and grass-oak woodland (left). Slope morphology on the two terrain-types is controlled by notably different geomorphic processes.

The climate is characterized by high annual rainfall (125-250 cm) that occurs mostly from October through April; the majority of the sediment transport occurs each winter during the two to six most intense storms. Infrequent high-intensity storms of long duration, which are major sediment-transporting events, recur every 100-500 years. One such storm, which occurred in December 1964 (Waananen et al. 1971), caused widespread landsliding and channel aggradation in numerous drainage basins in the California northern Coast Ranges, including the Van Duzen; the 1964 storm serves as a major focus of this study.

The two drainages in the study area are the upper Van Duzen River and the upper portion of the South Fork Van Duzen River (fig. 1). These rivers have classical concave profiles with steep, narrow headwater drainages. At their downstream ends, both rivers have wide alluviated valleys. A distinguishing geomorphic feature is that both rivers are perched above the lower drainage basin of the Van Duzen by a prominent knickpoint that forms a baselevel midway down the drainage basin. An erosionally resistant channel of Franciscan melange boulders from lower drainage-basin hillslopes causes this knickpoint. The knickpoint impedes downcutting of the upper drainage-basin rivers, which effectively maintains the wide alluviated valley at a midbasin location (Kelsey 1980).

LANDSCAPE FORMATION BY DEBRIS AVALANCHING

Rapid, episodic, and shallow debris avalanches are the main type of slope failure in the steep headwater basins of the study area. The avalanches scour down into fractured and usually partially weathered bedrock; avalanche thickness ranges from 1.0 to 4.5 m, and averages about 2.5 m. The failures leave a raw, unvegetated slide scar that may take as much as a century to revegetate because all soil is removed (fig. 3). Parent material is predominantly bedded metasiltstones which become fluid upon failure. The avalanches occur on mid or upper slopes and coalesce into channel-confined debris torrents as the material moves downslope (Swanston 1970). The avalanche scar generally has a straight profile below the crown scarp. Little colluvium remains perched on the scar, and most of the coarse debris initially deposited in the headwater channel moves further downstream in a more gradual manner by fluvial transport.

The straight profile of forested slopes in the study area, the lack of extensive fluvial dissection of these slopes, and the substantial amount of landsliding that occurred as a result of the 1964 storm (Kelsey 1980), all strongly suggest that debris avalanching is the mode of landscape formation on forested sandstone slopes of the study area. During the intense storm of December 1964, many of the slopes showing the most obvious evidence of geologically young, prehistoric sliding did not fail; most of the 1964 failures were on older slopes. The one large (0.34 km$^2$), raw, prehistoric landslide scar (fig. 3) and the basins with the morphologically youngest crown scarps and the most recent debris torrent deposits all remained stable during the storm, whereas other slopes not showing prominent features of recent prehistoric sliding did fail in 1964. The fact that the oldest slopes appear most susceptible to failure suggests that major climatic events are more likely to affect slopes that are revegetated and becoming progressively more weathered, rather than recently failed slopes that are in the process of recovery.

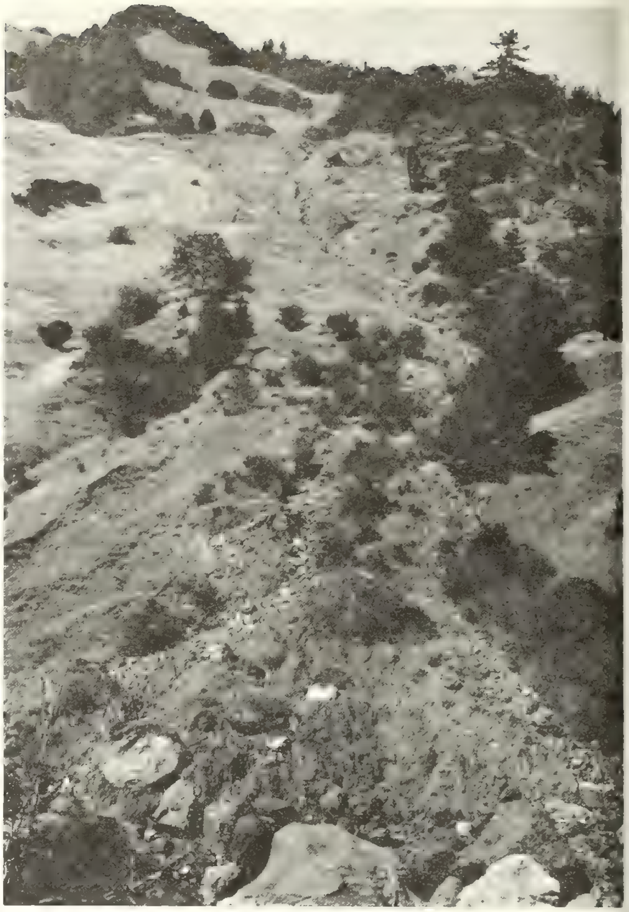


Figure 3.--Mule Slide (0.34 km$^2$) in the headwaters of the Van Duzen River. This debris avalanche failed in prehistoric time--possibly around 1790, based on an aggradation event that occurred 3-4 km downstream at about then. Note the bare patches along the tributary immediately downstream of the avalanche scar, which attest to the debris torrent that was generated by the avalanche. This tributary has a flat valley floor, 45-90 m wide, that is filled with alluvium from the debris torrent. Despite the fact this avalanche is at least 150 years old, it shows little evidence of revegetation, suggesting long recovery times for such slope failures.

## MOVEMENT OF DEBRIS AVALANCHE-DERIVED SEDIMENT DOWN STREAM CHANNELS

The upper drainage basin of the Van Duzen basin offers an excellent opportunity to study some aspects of the movement of sediment from slopes to headwater channels where complicating factors of large drainage area and heterogeneous rock units are eliminated. In the headwater area, sediment moves rapidly off the hillslopes, then much more slowly in the channels. The rate and path of sediment transport from slope through upper drainage-basin channels to the lower drainage basin are dependent on the frequency of mass slope failures and on the sites of initial and subsequent deposition of landslide debris in the valley bottom.

Debris avalanches greater than 30 000 $m^3$ occurred at the heads of nine headwater tributary basins during the December 1964 storm (fig. 4). Avalanche sites were all in virgin forest unaffected by timber harvesting or road building. The avalanches ranged in area from 0.5 to 5.5 ha, scoured into weathered bedrock, and were between 1.0 and 4.5 m thick. Total amount of avalanche debris discharged into the headwater channels of the two upper drainage basins was 4 041 000 metric tons. In addition to sediment delivered from the slopes by avalanching, severe bank erosion of older 18- to 30-m-thick debris-torrent fill-terraces on the channel margins of the upper South Fork occurred, which further contributed to channel aggradation. I studied the movement of sediment derived from these avalanches and channel fills for the 10 years after the flood by a combination of field mapping and interpretation of time-sequential sets of aerial photos. I analyzed individually the first-order and second-order headwater channels of the Van Duzen and the South Fork Van Duzen, and next highest order channel reaches, to determine the amount of debris contributed by avalanching and by erosion of previously stored channel fill to downstream aggradation, the depth of aggradation in headwater channels immediately after the flood, and the rate at which alluvium moved farther downstream once initially deposited (table 1). Methods of mapping along the channels are described in Kelsey (1980).

Sediment delivery from steep headwater slopes to sites of initial deposition occurs rapidly, but subsequent downstream movement of sediment is much more gradual. In the South Fork and Upper Van Duzen headwater basins respectively, 67 and 81 percent of the sediment mobilized from slopes and stored channel fill in December 1964 was initially deposited in the headwater channels (table 1), and the remainder was transported downstream by the flood. Aggradation in headwater channel reaches immediately after the flood ranged between 1.0 and 4.5 m. In both headwater basins, 75 percent of the aggraded sediment moved farther downstream in the next decade (fig. 5), and its migration could be clearly traced by field mapping and by inspection of sequential aerial photos. The longitudinal profiles of the South Fork Van Duzen and upper Van Duzen drainage basins (figs. 6 and 7) show the sites of initial debris torrent deposition and the sites of maximum channel aggradation at different times after the

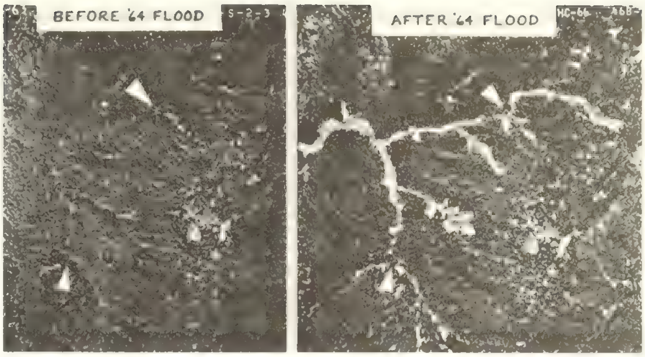


Figure 4.--Comparative aerial photographs of the headwaters of the South Fork Van Duzen River showing slope conditions before and after the 1964 storm. The photos were taken in the summers of 1963 and 1966; the white arrows show identical locations on the two photos. The large, elongate debris-avalanche scars grade downslope into channel-confined debris torrents; these torrents scour and widen channels and deposit thick alluvial fills at their downstream depositional ends (see fig. 5). Bank erosion on channel margins downstream from initial debris-torrent deposition occurred as the coarse sediment was subsequently mobilized downstream; this erosion has caused smaller debris slides along the channel that are visible in the postflood photo.

Figure 5.--Upstream view (August 1975) at the confluence of the South Fork Van Duzen River with Red Lassic Creek. Note sheared-off stumps of trees originally buried with alluvium after the December 1964 storm (3.6-m stadia rod leaning against middle stump for scale). The source of the alluvium was debris avalanches immediately upstream. Behind the stumps is an alluvial fill deposit from a former debris torrent; fills such as this one are now preserved along the valley margins at localities protected from frequent stream corrasion. Alluvial fill from the 1964 debris-avalanche events was in turn nested alongside the older fill shown here.

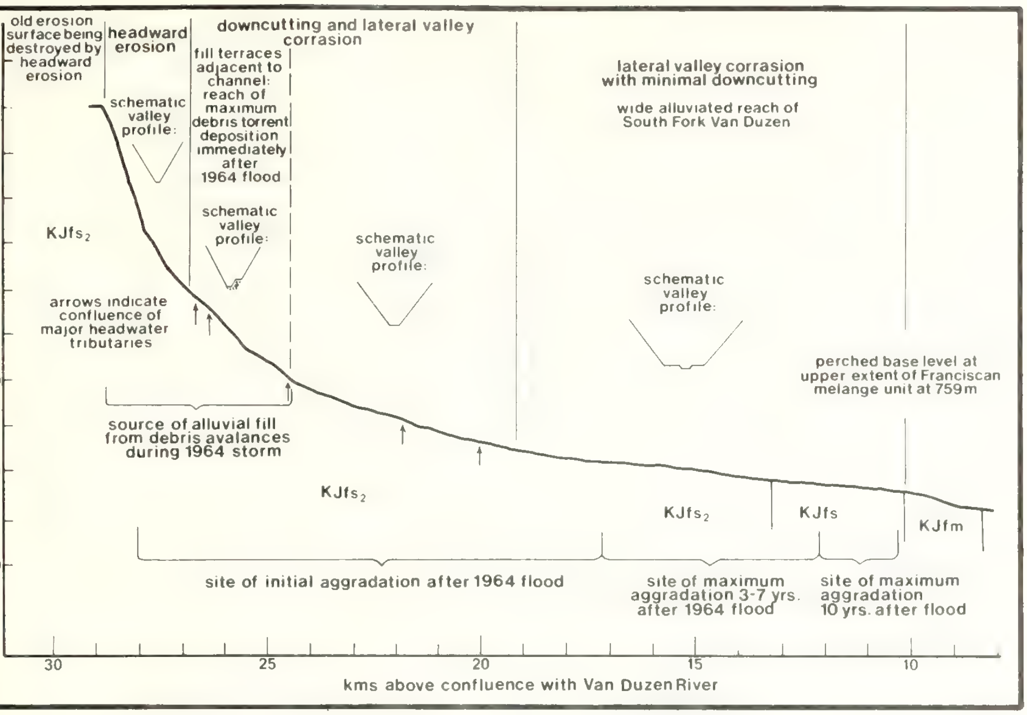
Table 1--Mobilization of alluvium in the headwater reaches of the Van Duzen River, 1964-75, as a consequence of the December 1964 storm

| Channel reach, going in downstream direction | Amount of landslide debris discharged directly into reach during the December 1964 flood $\rho = 1.92$ g/cm$^3$ | Estimated amount of alluvial channel fill, stored in floodplain and fill terraces, remobilized by the December 1964 flood $\rho = 1.92$ g/cm$^3$ | Initial aggradation as a direct consequence of the December 1964 flood: Average depth of fill | Initial aggradation as a direct consequence of the December 1964 flood: Amount of fill $\rho = 1.92$ g/cm$^3$ | Amount of degradation as of 1975: Average depth of scour | Amount of degradation as of 1975: Amount of fill removed $\rho = 1.92$ g/cm$^3$ |
|---|---|---|---|---|---|---|
| | Metric tons | Metric tons | Meters | Metric tons | Meters | Metric tons |
| South Fork Van Duzen River: | | | | | | |
| Headwater Reach A 2d order | 218 000 | -- | 1.8 | 34 000 | 1.7 | 31 000 |
| Headwater Reach B 1st order | 490 000 | -- | 2.1 | 19 000 | 1.7 | 15 000 |
| Headwater Reach C 2d order | 783 000 | [1]210 000 | 2.7 | 132 000 | 2.1 | 100 000 |
| Headwater Reach D 2d order | 36 000 | -- | 3.4 | 27 000 | 2.9 | 24 000 |
| Channel Reach E 3d order | 75 000 | [1]249 000 | 4.3 | 1 059 000 | 3.2 | 794 000 |
| Channel Reach F 3d order | 49 000 | 36 000 | 1.4 | 264 000 | 1.1 | 198 000 |
| Tributary Reach G 2d order | 56 000 | -- | 0.5 | 9 000 | 0.5 | 9 000 |
| Channel Reach H 3d order | 22 000 | -- | 1.1 | 127 000 | 0.8 | 89 000 |
| Tributary Reach I 2d order | 490 000 | 32 000 | 1.7 | 209 000 | 1.2 | 157 000 |
| Channel Reach J 3d order | 8 000 | 9 000 | 0.8 | 80 000 | 0.6 | 56 000 |
| Tributary Reach K | 163 000 | -- | 2.1 | 2 000 | 1.5 | 1 000 |
| Total | 2 390 000 | 536 000 | | 1 962 000 | | 1 474 000 |
| Upper Van Duzen River: | | | | | | |
| Headwater Reach A 3d order | 479 000 | -- | 2.1 | 228 000 | 1.5 | 184 000 |
| Headwater Reach B 1st order | 197 000 | -- | 2.9 | 87 000 | 2.0 | 68 000 |
| Headwater Reach C 1st order | 90 000 | -- | 3.1 | 47 000 | 2.1 | 37 000 |
| Headwater Reach D 3d order | 767 000 | -- | 1.8 | 176 000 | 1.5 | 157 000 |
| Channel Reach E 3d and 4th order | 91 000 | -- | 1.8 | 451 000 | 1.4 | 350 000 |
| Channel Reach F 4th order | 27 000 | -- | 1.3 | 110 000 | 0.9 | 92 000 |
| Channel Reach G | 0 | -- | 0.5 | 70 000 | [2]0.7 | [2]101 000 |
| Total | 1 651 000 | | | 1 169 000 | | 888 000 |

[1] Values for alluvium stored in fill terraces derived from deposition of the Red Lassic debris avalanche.

[2] Contrary to the rest of the column, these values indicate amount and depth of AGGRADATION in the downstream-most reach, which aggraded as alluvium moved downstream.

1964 storm. Migration rates for the aggradation maxima in the upper channel reach of each drainage basin were 8.9 km/10 years in the upper Van Duzen (gradient = 0.015) and 13.7 km/10 years in the steeper South Fork (gradient = 0.027). As the pulse of sediment moved downstream, bank cutting occurred, and this bank erosion was especially extensive along the wide floodplains of the South Fork at the lower end of the study area (fig. 6). In the wide, 6.5-km long, alluviated valley of the South Fork, which starts 8 km below the site of the 1964 avalanching, aggradation-induced lateral corrasion eroded 35 ha of floodplain between December 1964 and 1974. Floodplain banks retreated as much as 110 m as the active channel widened. Seventy-nine percent of this erosion occurred by June 1966, indicating most of the bank retreat was a direct consequence of the flood and the initial pulse of aggradation. After 1966, reaches of maximum bank retreat moved downvalley with the locus of maximum aggradation (Kelsey 1977).



igure 6.--Longitudinal stream profile of the South Fork Van Duzen River showing the tributary sources of ebris avalanching, sites of initial debris-torrent deposition after the December 1964 flood, and migra-ion of maximum channel aggradation after the 1964 storm. The channel profile is segmented into reaches f similar channel form and geomorphic process. (KJfs$_2$ is metasandstone; KJfs is sandstone; KJfm is elange.)

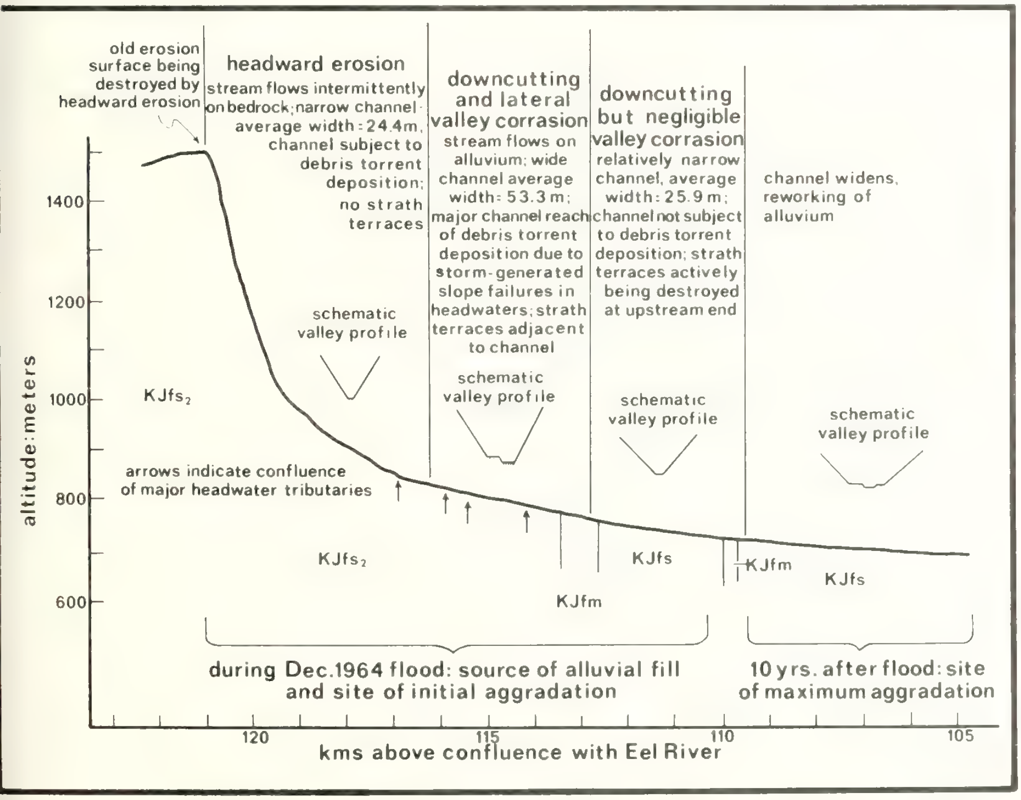


Figure 7.--Longitudinal stream profile of the upper Van Duzen River showing the dominant geomorphic processes operating along the channel, and the tributary sources of avalanching and sites of deposition during and after the December 1964 storm and flood. (KJfs$_2$ is metasandstone; KJfs is sandstone; KJfm is thin shear zones of melange.)

Aggradation and bank erosion in the South Fork occurred concurrently with changes in channel pattern from a single meandering stream to a braided system of channels. A comparison of channel widths measured by the U.S. Land Survey in 1872 with 1963 and 1974 channel widths along the wide valley of the South Fork indicates that in the period 1872-1974, channels increased in width anywhere from 200 to 2,000 percent and practically all this erosion occurred between 1963 and 1974.

Channel recovery from such increases in width (i.e., channel downcutting, decreased channel width and revegetation of floodplains) is a slow process that along the South Fork Van Duzen probably will take longer than 25 years and may take more than a century. Along channels elsewhere in the California Coast Ranges, I have observed that after 15 years, many 1964 flood bars are becoming revegetated and are being isolated by downcutting. On other channel reaches where landslide contributions were greater or landslide activity continued after 1964, downcutting is a slower process and flood bars are still being overtopped by discharges that recur every year or two. Such long recovery times for the South Fork Van Duzen or other channels that carry landslide-delivered pulses of sediment stand in marked conflict with Wolman and Gerson's (1978) contention that stream channels in mountainous, temperate climates recover relatively quickly (10 years) after a major climatic event. Infrequent events of large magnitude, such as the 1964 storm and flood, can leave a long-lasting imprint on channel morphology when such a climatic event triggers slope failures that deliver massive amounts of alluvium to stream channels.

Movement of coarse sediment through upper drainage-basin channels results in a systematic downstream change in channel morphology and valley profile (figs. 6 and 7). Because the headwater basin area is underlain by a fairly homogeneous Franciscan sandstone unit, geomorphic processes operate in a reasonably simple and predictable manner, given stable climatic conditions.

The headwater tributaries of both drainage basins are actively eroding into an old upland surface, and the dominant geomorphic process is active headward erosion along first-order and second-order tributaries where stream gradients are steepest, stream channels are narrowest, streams flow on bedrock, and little alluvium is stored in the channels. The tributary slopes periodically undergo debris-avalanche failures, which generate debris torrents. Where the first- and second-order tributary streams enter the third- and fourth-order South Fork and upper Van Duzen Rivers, channel width increases markedly. Voluminous amounts of coarse alluvium enter these river reaches from tributary debris torrents. These pulses of alluvium promote lateral corrasion of the valley walls, which leads to the formation of strath surfaces (fig. 7). At this point of channel widening, the dominant geomorphic process in both rivers changes from headward cutting to alternating downcutting and lateral valley corrasion. Stream gradient decreases noticeably where the channel widens (figs. 6 and 7).

Alluvial terraces border upper reaches of the South Fork and upper Van Duzen only in their wide channel reaches where lateral corrasion occurs. In the upper Van Duzen, the terraces are strath terraces preserved by uplift of the planated bedrock channel floor. The straths have an alluvial veneer that averages 7.5 m thick, which is about the depth of channel scour and fill during large floods; the surfaces range from 15 to 45 m above the present channel elevation (Kelsey 1977). Alluvial terraces in the South Fork channel are all fill terraces primarily associated with one exceptionally large prehistoric debris avalanche.

Downstream from the reach of alternative downcutting and lateral corrasion, the South Fork and upper Van Duzen channels have differing geomorphic characters because of geologic contrasts in the lower portion of the drainage basins. The South Fork continues to corrade laterally, and downcutting is minimal because of the proximity of the upper drainage basin baselevel on the South Fork (fig. 6).

The upper Van Duzen channel, downstream of the reach of alternating downcutting and lateral valley corrasion, narrows to about 26 m in response to the decreased sediment contribution to the channel (fig. 7). Coarse alluvium supplied by upstream debris torrents appears to have been sorted and winnowed out, and mapping of alluvial deposits suggests as much as 45 percent of the original channel alluvium has been transported downstream. The remaining bed material is no longer sufficient to cause substantial corrasion of the bedrock valley walls. Potential transport capability exceeds sediment supply, so downcutting is the dominant process along this channel reach. At the upstream end of this reach, strath terraces are being destroyed by downcutting as erosion continues headward (fig. 7). Further downstream on the upper Van Duzen, the gradient moderates, the valley floor widens, and the river flows in a broad alluviated valley similar to the South Fork.

This downstream progression of changes in both valley profile and geomorphic process in a headwater basin that is periodically supplied with slugs of coarse alluvial fill from avalanching is precisely the progression described by Bull (1979) in his discussion of the interplay of stream power (power available to transport the sediment load) and critical power (power needed to transport the sediment load) in determining the efficiency of sediment transport and the shape of the valley profile. In steep, v-shaped headwater tributaries where stream power exceeds critical power, sediment movement downstream is rapid. Where gradient begins to moderate and low-order streams converge and supply large quantities of sediment to higher order channels, critical power equals stream power in the long-term average. Downcutting and lateral valley corrasion at these sites alternate as the dominant geomorphic processes and both strath and fill terraces can form and be preserved. Some coarse sediment is moved rapidly through such channel reaches, but other coarse alluvium, which I estimate to be between 5 and 20 percent, becomes entrapped in erosionally isolated fills, and residence times range from hundreds to many thousands of years.

In the lowest gradient, highest order stream reaches of both upper drainage basins, wide alluviated valleys occur where stream power is substantially less than critical power most of the time. As a result of infrequent, high discharges, the wide alluviated valleys aggrade, but in the long term, the stream gradually scours as it reworks and transports coarse alluvium downstream. Residence times of different pockets of alluvium on wide alluviated valley floors are difficult to determine and vary greatly depending on the position of the alluvial deposits.

## RECURRENCE INTERVALS OF DEBRIS AVALANCHING AND RESIDENCE TIME OF ALLUVIUM IN CHANNELS

Large-scale mobilization of channel fills, such as that of the December 1964 storm, only happen when storm runoff is charged with slugs of sediment generated by hillslope avalanching. A large flood-producing storm alone is not sufficient to initiate substantial alluvial reworking in higher order channels. The storm must trigger hillslope failures that contribute coarse debris to channel. A 1955 storm in the Van Duzen was of comparable magnitude to the 1964 storm (Harden et al. 1978) but the absence of significant slope failure in 1955 resulted in negligible channel change (Kelsey 1980).

Recurrence-interval estimates of debris-avalanche events in headwater channels are valuable in determining the average interval of channel stability between major sediment-transporting events. These recurrence intervals can best be approximated by studying the alluvial stratigraphy of debris-torrent fills at the mouth of headwater tributaries, where series of truncated alluvial fans from prehistoric torrents are preserved as forested fill-terraces. Detailed studies using dendrochronology and $C_{14}$ dating at two such sites where a series of three fills are nested along valley wall margins suggest episodes of major avalanching occurred in these headwater drainages at intervals greater than 300 years but probably less than 2,000 years, though minor avalanches and smaller debris torrents occurred more frequently (Kelsey 1977, 1980). The dating of channel fills in the upper Van Duzen, combined with data collected by Helley and LaMarche (1973) from a similar study in nearby drainages, shows that storms capable of triggering large landslides and mobilizing substantial amounts of alluvium occur, on the average, once every 100 years in at least one large drainage basin in the northern Coast Ranges. Especially severe storms that cause widespread avalanching and aggradation throughout the northern Coast Ranges are more infrequent, and the data suggest these storm events do not occur as frequently as 100 years, and probably occur only once every 500 or more years. Convincing evidence on hillslopes and in channels of such large magnitude events is not preserved, however. Note that the rate of recurrent slope failure is greater adjacent to third- and fourth-order streams in the lowest reaches of the headwater area where streambank corrasion accompanies each episode of channel aggradation, causing frequent but much smaller debris sliding on the footslopes.

These recurrence-interval estimates are a first step in estimating the residence time of alluvium stored in Van Duzen headwater channels. The following rough estimates are for second- and third-order channels of the study area. The estimates are based on the areal distribution of fills in the channels, as well as on the estimated debris-avalanche recurrence intervals. If sediment remains in the active channel, defined by the mean annual flood, residence time is short, probably less than ten to tens of years. Sediment may also be deposited in thick debris torrent fills. Fills adjacent to the active channel will probably be removed by bank erosion from large storms that recur, on the average, once every century. Fills that are further removed from the active channel and are nested against the valley margin may become isolated by incision and stabilized by forest cover. These fills may remain intact for many hundreds or a few thousand years until avalanches from subsequent large storms send a sediment-charged flood surge through the valley, removing portions of the fills and replacing them with new material. Sediment deposited on strath surfaces that are subsequently isolated from the stream by downcutting into the bedrock have much longer residence times. Alluvium stored on these strath surfaces can survive from a few thousand to as much as ten thousand years until destroyed by debris sliding on the valley sideslopes. Further work is needed to determine what percentage of the coarse alluvium is subject to the different residence times.

## HILLSLOPE EVOLUTION AND THE RESIDENCE TIME OF DEBRIS ON HEADWATER SLOPES

My hillslope model for the Van Duzen headwater area, based on observed slope morphologies, sizes of recent avalanches, and alluvial stratigraphy, is that headwater slopes are sculpted by relatively large debris avalanches, and these debris avalanches over time affect all the headwater drainage areas (Kelsey 1980). Both the extent of avalanching during the 1964 storm and the presence of relict avalanche scars that encompass entire first-order basins argue strongly for the model. This model stands in contrast to that of Dietrich and Dunne (1978) and Lehre (this volume), in which debris avalanches and debris flows are initiated from bedrock hollows or swales which occur in only a small part of the landscape, and that other processes, such as creep, surface erosion, and tree throw, feed debris to the swale areas. Both models probably do represent actual conditions for forested drainage basins in different environments. The duration of time between major failures at a specific site is dependent in one case on the rates of hollow filling by creep, surface erosion, and tree throw, and in the other case, by the rate of soil formation and weathering of the regolith at the site of avalanching. Frequency of failure at a site is probably greater in the case of hollows because hollow-filling processes are faster than in situ weathering of newly exposed material. I believe that differences in uplift rate are important in determining which mode of landscape evolution is in operation, and relatively high uplift rates in the Van Duzen favor debris-avalanche sculpted topography. Important, but poorly understood variables, such as the rate of creep and the frequency of debris avalanche or debris flow failures, make further refinement of either model difficult at this time.

The residence time for slope debris is the approximate interval for the entire surficial slope mantle to be mobilized by catastrophic landsliding at least once, assuming the persistence of present climatic and tectonic conditions. The estimate of residence time therefore applies only to forested headwater slopes from ridge tops to a boundary about 50 m above perennial streams, which is that boundary above the immediate influence of channel corrasion and downcutting. I have estimated a residence time for the surficial mantle by knowing the area unvegetated from recent avalanching, and applying an estimate of recurrence interval for this amount of avalanching. In 1975, between 2 and 3 percent of the headwater slope area was exposed from avalanching, and--based on alluvial stratigraphic studies cited above--I assume this extent of avalanching occurs every 500 years or more. Table 2 shows alternative estimates of residence time assuming that either 2 or 3 percent of the headwater basin area is denuded by avalanching every 500, 750, or 1,000 years, and that a different 2 or 3 percent is affected each time until the entire weathered slope mantle is removed once. The last assumption is of course not entirely accurate, because one slope may fail twice while an adjacent one does not fail at all, but indications are that the slopes that have been stable the longest are most prime for failure. Estimates of residence times range from 17,000 to 50,000 years, which is one to two orders of magnitude greater than the residence time of debris once it reaches second- and third-order perennial stream channels.

Table 2--Determinations of residence time of the surficial slope mantle for six cases in the steep headwater region of the Van Duzen drainage basin.

| Case | Recurrence interval of major episode of avalanching | Portion of basin affected | Residence time of surficial mantle |
|---|---|---|---|
| | Years | Percent | Years |
| I | 500 | 2 | 25,000 |
| II | 750 | 2 | 37,500 |
| III | 1,000 | 2 | 50,000 |
| IV | 500 | 3 | 16,700 |
| V | 750 | 3 | 25,000 |
| VI | 1,000 | 3 | 33,300 |

Using the estimates of residence time for the surficial slope mantle, an erosion rate for the headwater basin area can be calculated if we know the average thickness of the surficial layer lost by periodic avalanching. Avalanche failures in the headwater basins ranged between 1.0 and 4.5 m thick, and 2.5 m is a representative thickness. Assuming the average density of the rock and soil to be 1.92 g/cm$^3$, the above five different residence times (table 2) give the following range of erosion rates:

| Residence time | Erosion rate |
|---|---|
| Years | Tons/km$^2$ per year |
| 16,700 | 280 |
| 25,000 | 190 |
| 33,300 | 140 |
| 37,500 | 125 |
| 50,000 | 95 |

Sediment-discharge measurements in a 1.17-km$^2$, second-order forested drainage basin in the lower Van Duzen drainage basin gave a sediment yield of 45-180 t/km$^2$ per year (Kelsey 1977). This basin does not experience debris avalanching as frequently as the upper drainage-basin headwater region. Erosion rates in the headwater region could be 1.5 to 3 times as great, and probably range between 80 and 540 t/km$^2$ per year. Estimates of residence time of slope debris under current climatic and tectonic conditions therefore appear reasonable in light of the limited measured erosion rates.

## THE ROLES OF PERSISTENT VERSUS EPISODIC EVENTS IN MOBILIZING SEDIMENT

Persistent processes, such as fluvial sediment transport in gullies or streams by storm runoff, are low-magnitude events; episodic processes occur infrequently but generally mobilize relatively large amounts of sediment in short intervals. Episodic processes play a highly significant role in the Van Duzen headwater study area. Fluvial hillslope-erosion rates are quite low (Kelsey 1980). Periodic debris sliding or avalanching is the main process of sediment delivery to major channels and is the primary mode of landscape sculpture. In contrast, fluvial sediment transport, creep, and earthflow landslides are persistent processes that are particularly important in melange terrain in the lower Van Duzen basin. In this terrain, persistent processes are not only the most important sediment transporters but are also largely responsible for shaping the landscape. Only near large channels do episodic processes, such as debris sliding, slumping, or bank erosion, become significant in transferring debris from slopes to channels.

One of the long-standing questions in geomorphology is the importance of high-frequency/low-magnitude events versus low-frequency/high-magnitude events on transporting sediment and sculpting landforms. Geomorphic processes in the headwater study area point to the important role of infrequent, large-magnitude climate events, as compared to their role in other stream systems that flow through more stable geologic settings. In contrast to conclusions of Wolman and Miller (1960) that the low-magnitude geomorphic events appear to be by far the most important for sediment transport and landform evolution, large events in the Van Duzen headwaters have substantially modified landforms, both on the ope and in the channel, and have contributed rge quantities of sediment to channels. Wolman d Miller's analysis was largely based on diment yields from gaging stations, whereas this udy addresses hillslope erosion rates caused by valanching and investigates channel changes from e interplay of avalanching and the movement of diment stored in channels. The latter approach cuments the importance of infrequent episodic ents in erosion of the Van Duzen headwater sins. In this study, sediment delivered to annels by avalanching apparently can account for most the entire estimated erosion rate of adwater basins. In addition, the infrequent and igh-magnitude runoff events are also responsible r the major changes in sediment storage, which count for the significant long-term changes in annel morphology.

## RAINAGE-BASIN RECOVERY AND HIGH-MAGNITUDE, PISODIC EVENTS

here episodic, high-magnitude events are mportant, the recovery times on hillslopes and in hannels after large landslides or aggradation vents become significant. Recovery means evegetation of hillslopes and restitution of hannel width and depth to that configuration rior to rapid, storm-induced change.

he recurrence interval of large-scale geomorphic vents is influenced by whether or not major torms occur, on the average, while hillslopes and hannels are still recovering. If a large part of he basin is in early vegetative recovery, igh-magnitude events may have greater effect. In he case of the 1964 storm in the Van Duzen eadwaters, there were no areas just beginning to evegetate. Therefore, failure of recently xposed slopes was negligible. The disturbance requency in a basin probably increases as the roportion of a basin in early vegetative recovery ncreases. However, once a failed slope has evegetated but prior to significant weathering of he newly exposed surface material, the slope is ot highly prone to failure. For this reason, oung, revegetated landslides in the Van Duzen eadwaters were not affected by the 1964 storm. he effect of recovery time on disturbance requency is not easily determined because of the hort historic record, but if we substitute space or time, that is, look at a large area, the 1964 torm apparently did not hit an area in the rocess of recovery from a previous widespread, igh-magnitude event. This pattern is true both or the 160-km$^2$ study area and for a much larger rea, about 1500 km$^2$, that encompasses the upper rainage basins of many northern California Coast ange basins. Had the same storm hit an area in idespread recovery from a previous storm, isturbance probably would have been significantly reater.

he frequency of disturbance is probably increased y landuse. Intensive landuse in the Coast Ranges ince 1860--especially road building, timber arvesting, and grazing--has exposed bare soil or eathered bedrock and ruptured the vegetation at. In addition to the vegetative and channel ecovery from climatically induced slope failures n undisturbed slopes, the disturbed areas may also be prone to further failure, especially along major channels and on headwater slopes. The amount of area in some stage of vegetative recovery is therefore much greater than a century ago. Major climatic events are now likely to trigger more frequently both small landslides directly attributable to landuse as well as large landslides only indirectly related to landuse.

## SUMMARY

Two third-order, forested basins that comprise the headwaters of the Van Duzen River provide an opportunity to study the movement of sediment on hillslopes and in channels. Sediment is mobilized on hillslopes primarily by debris avalanches that deliver material to first- and second-order channels by debris torrents. After a debris avalanche occurs, residence time of the newly exposed surficial slope material ranges from 15,000 to 50,000 years. Sufficient soil weathering occurs during this residence time so that slope failure is likely to recur during a large storm event.

After sediment reaches a stream channel by avalanching, its residence time is dependent on the site of sediment deposition and the recurrence interval of upslope debris avalanching that serves to remobilize channel-stored fill and deposit new fill from the slopes. Debris avalanches in a first- or second-order basin recur about every 300-500 years. Therefore, flushing of the more accessible fills adjacent to the active channel occurs with the same frequency. Channel fills nested along valley walls further removed from the active channel move less frequently and may remain in place for hundreds or a few thousand years. Active channel deposits move on the scale of every year to at least once a decade. Alluvium perched on strath terraces that have been isolated from the channel by uplift only becomes reincorporated in the active channel by sideslope debris sliding. Such sliding probably recurs at any one site every 1,000-5,000 years. The proportion of channel alluvium that is active compared to that alluvium stored in fills or on bedrock straths is hard to estimate, and more work is clearly needed. Residence time of debris on hillslopes, however, is usually two orders of magnitude longer than residence time of alluvium stored as fill in channels.

Infrequent, high-intensity storms trigger avalanches that sculpt the landscape and set in motion the redistribution of sediment stored in channels. More persistent and smaller storm events probably are responsible for transporting the greater volume of sediment in channels. Infrequent, episodic events, however, are responsible for major shifts in sediment storage, and therefore these events are the catalysts for the significant changes in channel morphology that occur on a time scale of thousands of years.

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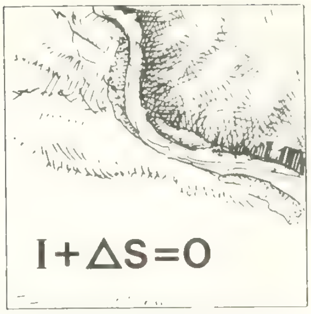

# Sediment Transport and Channel Changes in an Aggrading Stream in the Puget Lowland, Washington

Mary Ann Madej

ABSTRACT

Recent land-use changes increased sediment yield in a fourth-order stream in western Washington from 22 t/km$^2$ per year to 185 t/km$^2$ per year. In response, channel width increased and depth decreased, but channel gradient and mean flow velocity remained about constant. As a result of channel changes, sediment transport rates increased from 500 t/year to 4200 t/year. Active sediment constitutes 5 percent of stored sediment, and much sediment will be flushed from the system in about 20 to 40 years.

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Mary Ann Madej, Geologist, National Park Service,
Redwood National Park, Arcata, California 95521.

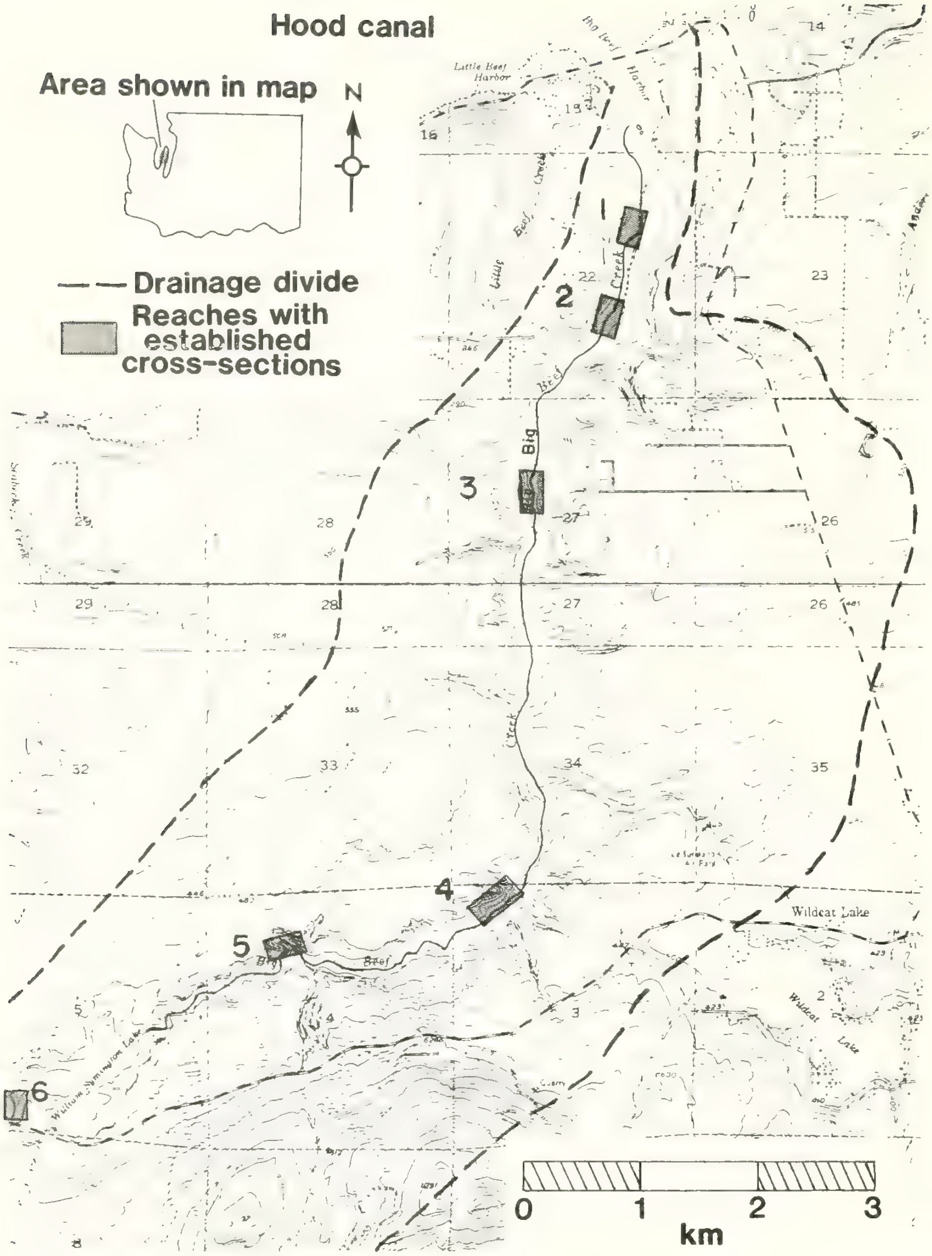

Figure 1.--Map of lower Big Beef Creek drainage basin showing reaches with established cross sections.

INTRODUCTION

The sediment load of a stream is determined by such characteristics of a drainage basin as lithology, vegetation, precipitation, and land use, and it enters the stream system by a variety of erosional processes. If stability is to be maintained, an equilibrium must exist between sediment entering the stream and sediment transported through the channel. Changes in sediment load can upset this balance and result in physical and biological changes in the stream system.

The purpose of this study is to determine the source and volume of sediment introduced into a stream, and its subsequent distribution, rate of movement, and influence on channel geometry. Three approaches were used. First, a sediment budget quantifies the amount of sediment introduced into the stream channel. Second, sediment-transport equations predict how much sediment moves under conditions of various channel morphologies. Third, survey measurements indicate the volume and distribution of the deposited sediment.

FIELD AREA

Big Beef Creek, a gravel-bedded stream, was selected for study because high rates of sedimentation and channel instability during the last 10 years were evident and baseline data were available from records kept at the University of Washington Fisheries Research Station at the mouth of the creek. This fourth-order stream drains an area of 38 km$^2$ on the Kitsap Peninsula in Puget Sound, western Washington (fig. 1). More than 85 percent of the drainage basin is forested with second-growth western red cedar (Thuja plicata Donn ex D. Don), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), and associated species. The climate is characterized by cool, dry summers and mild, wet winters. Annual precipitation (predominantly rain) ranges from 1300 to 1700 mm, and most major storms occur between December and March.

The dominant surficial geologic unit in the drainage basin dates from the Vashon (late Wisconsin) glaciation. A mantle of compact till, composed of a bluish-gray mixture of cobbles, pebbles, and silt and clay, covers much of the area. In addition, poorly sorted recessional outwash sands and gravels form many of the surface deposits in the Big Beef Creek drainage basin.

The upper 15 $km^2$ of the Big Beef Creek basin has a low channel gradient (0.2 percent), an average hillslope gradient of 5 percent, and drains into an artificial lake. Because the lake acts as a sediment trap for suspended and bedload particles from the upper basin and most runoff and sediment discharge are generated below the lake, this study only considers a sediment budget for the lower drainage basin, where average channel gradient is 1 percent and hillslope gradients range from 10 to 70 percent. Drainage density below the lake is 2.5 $km/km^2$, as measured on 1:12,000 aerial photographs.

In 1969, the U.S. Geological Survey established a gaging station 1.6 km above the mouth of Big Beef Creek. The frequency of annual peak discharges was compiled from daily discharge records. The 10- and 50-year floods are about 30 and 56 $m^3$/second, respectively. No flood has exceeded 30 $m^3$/second in the past 10 years, and regional records indicate that no 50-year floods have occurred in the last 25 years. Thus recent changes in the Big Beef Creek basin occurred under fairly normal climatic patterns.

The principal activities in the drainage basin since the 1850's have been logging and some cattle grazing. Most virgin timber was logged by 1930 and a resurgence of logging activity occurred in the mid-1950's, when harvest of second-growth timber was initiated. Urban development is becoming widespread and this decreases the amount of forested land as well. In 1942, 3 percent of the land was deforested, by 1965 the figure was 12 percent, and today it is almost 20 percent. Likewise, road density tripled, from 1.2 $km/km^2$ in 1942 to 3.5 $km/km^2$ at present.

Personnel at the University of Washington Fishery Research Station noted heavy sediment deposition at the mouth of Big Beef Creek during the winters of 1966-67 and 1967-68; in the summer of 1969, the lower 500 m of the creek were channelized artificially. In 1970, a weir 2 m high was built across the mouth of the stream, which has acted as a small dam and has caused deposition of bed material for several hundred meters upstream of the weir.

## METHODS

### Cross-Section Surveys

Fifty-five cross sections along the main channel of Big Beef Creek were surveyed periodically from 1969-78 by Cederholm (1972) and me (fig. 1). Gradients of channel thalweg and water surface also were determined in several locations.

Detailed records of channel changes at one cross section were obtained from U.S. Geological Survey gaging station records for 1969-79. These records (Forms 9-207 and 9-275) consist of bimonthly measurements of width, cross-sectional area, mean velocity, discharge, and stage relative to gage datum.

### Regional Channel Geometry Survey

Because the channel geometry of Big Beef Creek was not determined until after the drainage basin had been disturbed by road construction and timber harvest, predisturbance geometry was predicted from a regional channel-geometry relation developed from relatively undisturbed drainage basins in similar geologic and geographic settings. Estimates of regional channel geometry were obtained by measuring bankfull width and depth, channel gradient, and sediment-size distribution and correlating them with drainage area at 20 sites on nearby streams (Madej 1978). Comparison of dimensions of the present Big Beef Creek channel with those from undisturbed channels draining the same area indicates the extent of changes in Big Beef Creek.

### Sediment Studies

Size distribution of sediment in the main channel and tributaries was characterized with the pebble-count method described by Wolman (1954). Samples of channel gravel, and hillslope and bank material were also collected, sieved, and weighed.

Sediment distribution within the main valley of the drainage basin was determined by mapping the location and volume of gravel bars, overbank sand deposits, terraces, tributary deltas, and debris fans. Aerial photographs at a 1:12,000 scale from seven flights between 1942 and 1976 allowed me to compare the locations and sizes of large gravel bars, log jams, and braided reaches through time. Area and location of mass movements were also mapped from photographs. Field checking provided more accurate estimates of volumes of material, as well as ages of mass-movement features dated by vegetation.

The size of the largest particle of bed material moved from a site by high flows during 1977 was obtained by observing marked rocks. Over 2,000 painted rocks were scattered on the upstream end of six gravel bars in the main channel and tributaries. The painted rocks ranged from 16 to 180 mm ($D_{50}$ = 64 mm). After high flows, the size of each rock found and the distance it had moved were recorded.

Bedload-transport rates were estimated by the methods proposed by Einstein (1950), Meyer-Peter and Müller (1948), and Emmett (1976). Dr. H. W. Shen of Colorado State University supplied a computer program of the Einstein Bed Load Function. This program was used to compute bed-material load under various conditions representative of the changing channel geometry from 1969 to 1978.

## RESULTS

### Measurements

Table 1 lists the results of cross-sectional surveys of six reaches during three periods. Generally, aggradation occurred in lower reaches, degradation in middle reaches, and little change occurred in upper reaches, as illustrated in selected cross sections (fig. 2).

Net aggradation occurred in Reach 1 above the weir. Between 1969 and 1976, the bed aggraded 0.5-1 m in the lower 300 m. Overbank flow deposited material over an area 70 m wide and built small levees to form new banks about 0.5 m above old banks. Alders rapidly revegetated overbank deposits and helped stabilize new banks. Overbank deposition is active, as indicated by several centimeters of sand burying young alders.

Net aggradation occurred in Reach 2 (fig. 2). The channel responded by assuming a more braided pattern in this reach and forming midchannel gravel bars. Bankfull width increased about 25 percent from 1973 to 1978, and bankfull depth decreased by a similar amount. Bankfull velocity (from U.S. Geological Survey records) remained about constant throughout this period.

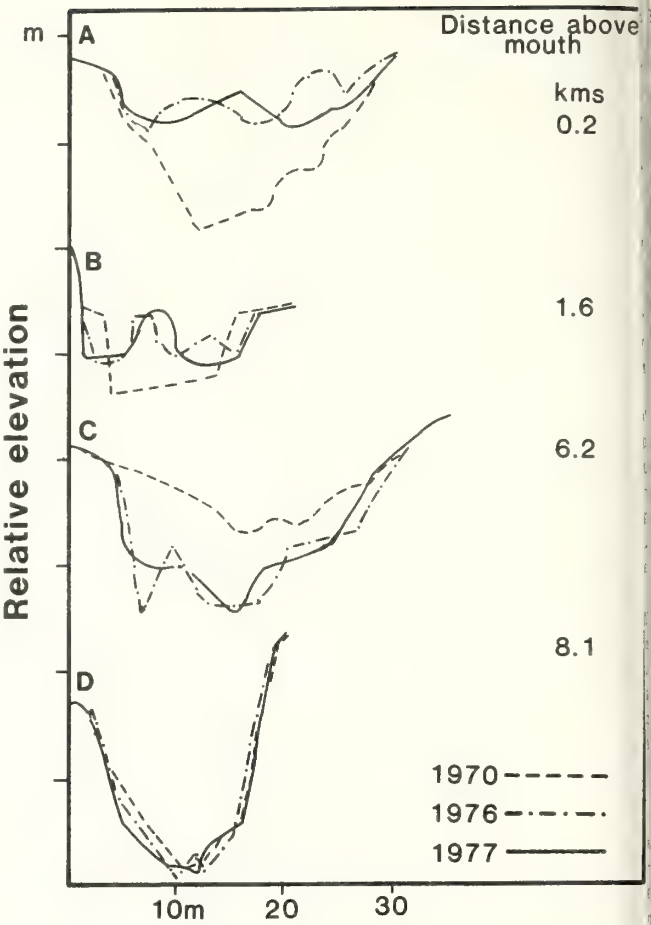

Figure 2.--Selected vertically exaggerated cross-sectional surveys in the main channel of Big Beef Creek.

Table 1--Results of channel cross-sectional surveys, Big Beef Creek, 1969-77

| Reach | Approximate distance above mouth | Change[1] in volume of sediment per unit length of channel (m$^3$/m of main channel per year) 1969-71 [2] | 1971-76 | 1976-77 |
|---|---|---|---|---|
| | Kilometers | | | |
| 1 | 0-0.8 | +5.05 | +0.88 | +1.26 |
| 2 | 1.1-1.6 | +1.05 | +0.34 | -0.86 |
| | | 1969-76 | | |
| 3 | 2.9-3.2 | -0.91 | | -0.05 |
| 4 | 6.2-6.6 | -1.33 | | +0.86 |
| 5 | 7.7-8.0 | -0.17 | | -0.01 |
| 6 | 9.6 | -0.16 | | +0.50 |

[1] Net deposition is indicated by a plus, net erosion by a minus.

[2] Surveys conducted by Cederholm (1972).

nk erosion and scour took place at several cations in Reaches 3 and 4, which may be a sponse to previous aggradation. Where roads are ill contributing large volumes of sediment, gradation and growth of gravel bars is apparent. contrast, the channel just below the lake each 5), which is located in a relatively disturbed area, showed little change.

ngitudinal surveys indicate that, in the lower km, channel gradient decreased from 0.090 to 085 between 1970 and 1977. Total channel length creased from 9785 to 10 010 m. Sinuosity creased from 1.30 to 1.32, and overall channel adient decreased slightly.

tterns of channel length changes correlate proximately with trends of cross-sectional anges. Where little cross-sectional change curred, channel length remained constant. In grading reaches, channel length increased; in e aggrading lower reaches of Big Beef Creek, annel length decreased.

e predicted and actual values of width for lower g Beef Creek differ considerably (fig. 3), though the difference is negligible for the per stream below the lake. Values for bankfull pth, channel gradient, and mean particle size e within limits of scatter in the regional ttern.

ter one winter, 53 percent of the painted rocks re found. Large particles (≥128 mm) did not ve as far as intermediate sizes (45-90 mm). rprisingly, small particles ( 45 mm) did not ve as far as those in the intermediate size ass. Many of these small particles were found dged behind large ones and were protected from rther movement. Mean distance moved by termediate-sized particles (45-90 mm) was 80 m.

stribution of sediment stored in the channel is sted in table 2. In side channels, the volume sediment above bedrock was measured. In the in channel, sediment was only measured to the pth of scour which was taken to be 0.4 m, the ximum depth of degradation in cross-sectional rveys.

g jams are temporary sediment traps for bed terial moving downstream. Logging activity may crease the number and magnitude of log jams in a ream channel, which in turn may increase the position of gravel and sand. In a relatively disturbed reach, four log jams were noted, or 5 jams/km of channel. In reaches with recent gging, the concentration was 12 jams/km and ese jams were larger than those in undisturbed aches. Log jams are associated locally with aided channels as the stream bends around the ms.

spended sediment was sampled periodically at 0, 8, and 1.5 km above the mouth. Using S. Geological Survey daily discharge data, I nstructed three suspended-sediment rating curves adej 1978). Average suspended-sediment load ar the mouth of Big Beef Creek is 2325 t/year 10 t/km$^2$ per year), assuming the basin above e lake does not contribute any suspended diment to downstream reaches.

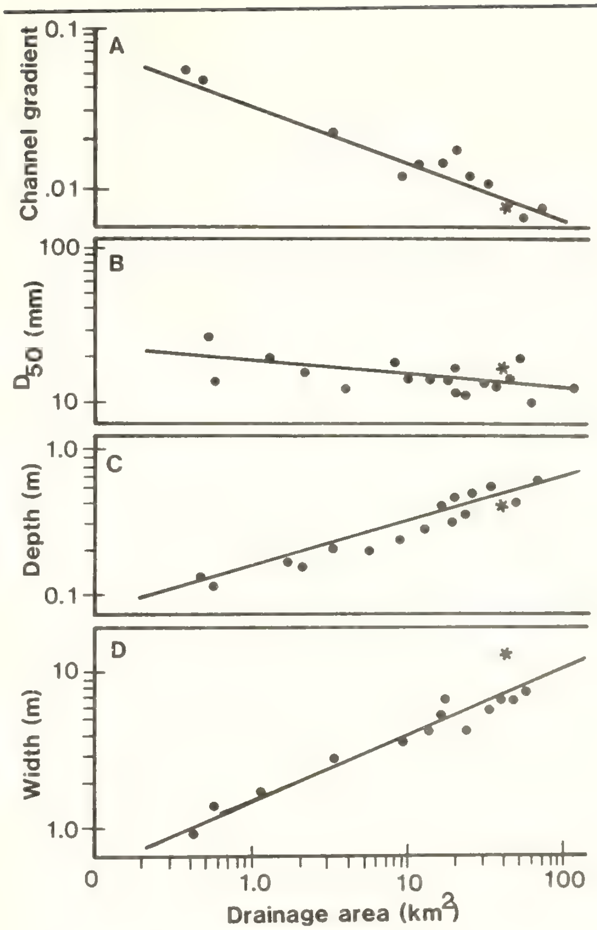

Figure 3.--Results of regional channel-geometry survey for Puget Lowland Streams (present dimensions for Big Beef Creek at 1.5 km are indicated by an asterisk).

Table 2--Distribution of alluvium in Big Beef Creek Basin (lower 23 km$^2$)

| Site of storage | Length of channels | Volume of sediment |
|---|---|---|
| | Kilometers | Cubic meters |
| 3d-order tributaries | 23 | $2.2 \times 10^4$ |
| 4th-order channel (to depth of scour) | 8 | $4.5 \times 10^4$ |
| (Active sediment in main channel[1/]) | -- | ($2.3 \times 10^4$) |
| Floodplain (to depth of scour) | -- | $4.5 \times 10^5$ |
| Total | | $5.2 \times 10^5$ |

[1/] Material that has been transported recently and is temporarily stored in unvegetated gravel bars and behind log jams.

CALCULATIONS

Sediment Budget

The amount of sediment entering Big Beef Creek can be quantified by examining the contribution of processes supplying hillslope material to channels. Sediment input in an undisturbed area was considered to enter channels by soil creep and hillslope failures. Rate of soil creep under edaphic and climatic conditions in the Big Beef Creek drainage basin was estimated from published creep rates for other areas (table 3). Three studies have been conducted in temperate areas receiving about the same annual precipitation as Big Beef Creek (1300-1500 mm), and the coarse soil textures in these study areas are similar to the Big Beef Creek basin. Average rate of creep for the top 15-25 cm of soil for all the studies lies within a narrow range, and a value of 1.5 mm/year was chosen as a reasonable estimate of creep rate in the Big Beef Creek drainage. In addition, tree throw (Dietrich et al., this volume) contributes the creep equivalent of 1.5 mm/year on steeper, wetter hillslopes. The extent of tree throw in the Big Beef Creek basin is not as great, and I estimate 1.0 mm/year of soil movement by tree throw, or a total rate of 2.5 mm/year.

Table 3--Rates of soil creep in temperate, humid climates

| Investigator | Precipitation | Gradient | Average soil creep (upper 15-25 cm) |
|---|---|---|---|
| | Millimeters/ year | Percent | Millimeters/ year |
| Everett (1963) | 990 | 25-65 | 0-2.2 |
| Young (1960) | 1400 | 35-55 | 1-2 |
| Kirkby (1967) | 1710 | 15-35 | 1-3 |

The most active layer of soil in terms of creep is the upper zone, which is influenced by such processes as root growth and decay, tree fall, and burrowing of animals. In the Big Beef Creek basin, the observed thickness of this active layer is about 0.5 m on hillslopes of 25-45 percent, and it has a density of about 1.7 t/m$^3$.

Total length of first- to fourth-order channels in the lower drainage basin is about 57 500 m. Because soil transported downhill by creep enters channels through shallow bank failures on both sides of a channel, the total amount of material introduced by creep is: $5.75 \times 10^4$ m x 2 x 0.5 m x 0.0025 m/year x 1.7 t/m$^3$ = 245 t/year = 10.6 t/km$^2$/year. This is a minimum estimate, assuming soil deeper than 0.5 m contributes little material in comparison to the more active surface layer.

Material discharged through soil creep is transported either as bedload or suspended load, depending on the size of material. Suspended-sediment samples collected in Big Beef Creek have a maximum particle size of 1 mm. Textural analyses of soil in the Big Beef drainage basin indicate that 40 percent of the active layer is greater than 1 mm. Thus, 147 t of material discharged into the channel through soil creep become suspended load, and 98 t is transported as bedload.

Some bedload may break down into particles small enough to be carried as suspended load. Tumbling experiments with rocks of similar lithology and size as material in Big Beef Creek (Kuenen 1956) show that 10 km of transport is insufficient to break down much material. Average rate of attrition is 0.1 percent/km of transport.

Large discrete hillslope failures are the second major contributor to a stream's sediment load. Field measurements of depth of slides averaged 0.6 m. During the last 10 years, 880 m$^2$ of land was affected by landslides that were not associated with roads, logging, or residential lots. So, the rate of mass wasting for undisturbed parts of the basin is: 880 m$^2$ x 0.6 m x 1.7 t/m$^3$ : 10 years = 90 t/year. These slides, which occurred on slopes >15 percent or at the headcuts of first-order channels, were representative of an area of 6 km$^2$ in the lower drainage basin, so the rate can be expressed as (90 t/year)/(6 km$^2$) or 15 t/km$^2$ per year. This rate is lower than estimates from other drainage basins in wetter, steeper environments (Swanston 1969, Dietrich 1975, Pierson 1977).

Because human activity significantly affected the remainder of the lower drainage basin, the rate of naturally occurring slides for the entire lower basin must be extrapolated from the rate of landsliding in the undisturbed sections. An area of 6 km$^2$ has hillslopes <15 percent, and probably does not contribute sediment through landsliding. The remaining 17 km$^2$ contributes 15 t/km$^2$ per year, or 255 t of sediment per year. This sediment is characterized by the size distribution of the average soil column. Thus, 153 t/year is suspended load, and the remainder becomes bedload.

Consequently, in an undisturbed state, sediment input into Big Beef Creek was:

| | |
|---|---|
| Soil creep - 245 t/year | 147 t/year of suspended load<br>98 t/year of bedload |
| Mass movements - 255 t/year | 153 t/year of suspended load<br>102 t/year of bedload |
| Total load - 500 t/year<br>(22 t/km$^2$ per year) | 300 t/year of suspended load<br>200 t/year of bedload |

This value for total sediment yield lies at the lower end of the range of sediment yields reported from drainages wetter, steeper, or both--such as 28 t/km$^2$ per year in western Oregon (U.S. Environmental Protection Agency 1971), 73 t/km$^2$ per year in southwest Alberta (Hollingshead 1971), and 105 t/km$^2$ per year in British Columbia (Slaymaker and McPherson 1977).

The Big Beef Creek drainage basin is no longer an undisturbed system because of changes in land use. In areas undergoing logging and road construction, rates of occurrence of mass movement may increase (Anderson 1954, Fredriksen 1970). In addition, processes such as sheetwash and rainsplash erosion--normally insignificant in humid, well-vegetated areas--may transport material from roads to channels.

Annual sediment contribution by disturbance-related landslides was quantified by mapping volumes of slides originating on roads and cut areas, and dividing volumes by the age of slides. These slides were smaller but more numerous than naturally occurring slides on valley sides. Between 1968 and 1977, an average of 845 t/year entered the stream channel through debris slides induced by land-use changes.

Roads are an additional source of sediment. Sheetwash on roadbanks and roadbeds, erosion of roadside ditches and sidecast material, roadbank gullying, and dry ravel from roadbanks are all active on roads in the Big Beef Creek basin. The volume of material eroded from roadside ditches was estimated in the field. Alluvial fans are not found at outlets of culverts draining ditches, and the largest painted rock moved in roadside ditches had a diameter of 64 mm. Thus, most eroded material probably reaches the stream channel. Roadside ditches contribute 440 t/year to the stream system.

Sheetwash carries sediment from roadbanks and roadbeds to stream channels. Few studies have directly measured amounts of sediment originating from roads, but these studies indicate the order of magnitude of sediment eroded from unpaved roads: Hornbeck and Reinhart (1964) - 9900 $t/km^2$ per year for fresh roads and 125 $t/km^2$ for abandoned roads; Diseker and Richardson (1961) - 20 000 to 60 000 $t/km^2$ per year; and Wolman and Schick (1967) - 20 000 to 50 000 $t/km^2$ per year. L. Reid and T. Dunne (University of Washington) are currently studying erosion on logging roads, and their results for moderately used and abandoned roads are of the same magnitude as those of Hornbeck and Reinhart. Of these estimates, the 9900 $t/km^2$ of Hornbeck and Reinhart seems the most reasonable to apply to the Big Beef Creek drainage basin, because these authors studied tractor-yarding skid roads under slope and precipitation conditions similar to those in the Big Beef drainage basin.

Although soil loss in the above studies was measured under a variety of conditions, sediment yields obtained were always far above the sediment yield in undisturbed areas. To apply these values directly to the Big Beef Creek drainage basin is risky because of variation in local conditions. Nevertheless, these values are useful estimates of soil loss from roads in the Big Beef Creek drainage.

Road prisms in the Big Beef Creek basin average 8 m in width. In 1977, 30 of the 65 km of unpaved roads were actively used. Using Hornbeck and Reinhart's values of sediment yield, I computed soil loss on roads to be: .008 km [(30 km x 9900 $t/km^2$ per year) + (35 km x 125 $t/km^2$ per year)] or 2410 $t/km_2$ per year. By examining the size distribution of lag deposits of the road surface, I estimated that 80 percent of the eroded material (1930 t) was transported as suspended sediment. Scour of roadside ditches contributes an additional 440 t/year. Thus a total of 2850 t/year is eroded from roads, of which 685 t is bedload.

The total sediment load of the stream is the sum of the contributions of natural hillslope processes and erosion processes from disturbed areas (table 4). Although these estimates in the sediment budget are approximate, their concordance with other measurements indicates they are of the correct magnitude. The estimate of 3000 t of suspended sediment/year compares favorably with the 2325 t/year obtained from suspended sediment rating curves. Estimated bedload input is 1200 t/year; the volume of sediment deposited in the lowest kilometer of Big Beef Creek between 1970 and 1977 was 4700 $m^3$, or 9000 t, an average load of 1400 t/year. Some of the 1400 t/year may represent sediment moving out of storage from upstream reaches, rather than bedload input from hillslope processes.

Table 4--Annual sediment input to Big Beef Creek

| | Suspended load | Bedload |
|---|---|---|
| | -Metric tons/year- | |
| Soil creep | 147 | 98 |
| Naturally occurring landslides | 153 | 102 |
| Disturbance-related landslides | 507 | 338 |
| Sheetwash on road surfaces | 1928 | 482 |
| Scour of inboard ditches | 264 | 176 |
| Total | 3000 | 1200 |

The computed sediment budgets suggest that total load of the stream increased from 500 t/year under undisturbed conditions to over 4200 t/year at present. Even if absolute values of sediment input are contested, the apparent contrast of sediment loads under undisturbed and disturbed conditions are large and significant.

### Sediment Transport

Once sediment enters a channel, it is transported downstream during high flows. Bedload transport represents work done by a stream and is a function of the boundary shear stress generated at any given moment and place. Boundary shear stress, $\tau_b$, produced by a fluid is calculated as:

$$\tau_b = u_* \rho \qquad (1)$$

where $u_*$ is related to velocity u at distance z from the channel boundary by

$$u = (u_*/0.4)\ (\ell n\ z/z_o) \qquad (2)$$

where $\rho$ = density of the fluid, $u_*$ = shear velocity, and 0.4 = von Karman's constant. The depth at which velocity apparently goes to zero as the channel bed is approached is the roughness length of the boundary, $z_o$, and is dependent upon particle size. It can be estimated by $D_{65}/30$, where $D_{65}$ is the grain diameter that is greater than 65 percent of the bed material (Graf 1971).

Bedload transport rates for the gaging site at Big Beef Creek (fig. 1) before and after disturbance were calculated from Einstein (1950), Meyer-Peter and Müller (1948), and Emmett (1976) (table 5). I have discussed their equations and the applicability to Big Beef Creek (Madej 1978). Dimensions of the undisturbed channel were estimated from regional channel-geometry results; those of the disturbed channel were obtained from survey measurements. Measured frequencies of discharge for each year were used. The three equations predict that an average of between 600 and 1400 t of bedload/year would be transported past the gaging site.

Table 5--Prediction of annual bedload transport i metric tons/year

| | Investigator | | |
|---|---|---|---|
| | Einstein (1950) | Meyer-Peter and Müller (1948) | Emmet (19 |
| Undisturbed channel | 645 | 580 | 34 |
| 1971 | 1510 | 1430 | 10 |
| 1972 | 660 | 1270 | 6 |
| 1973 | 500 | 1350 | 4 |
| 1974 | 1940 | 3255 | 9 |
| 1975 | 70 | 55 | |
| 1976 | 715 | 1090 | 3 |
| Mean annual transport after disturbance | 900 | 1410 | 59 |

INTERPRETATION

Present channel morphology allows greater bedload transport than the undisturbed channel (table 5). Analysis of boundary shear stress in the channel leads to the same conclusion. An increase in stream-channel capacity must be caused by an increase in $\tau_b$. Using U.S. Geological Survey velocity and discharge measurements, I compared magnitude and distribution of shear stresses at four sites near the gaging station at equivalent discharges over a 4-year period (Madej 1978). Figure 4 shows the results of this analysis at one site, where erosion occurred at the right bank and the channel was 2 m wider in 1975 than in 1971.

Several common characteristics were found in the four analyses. The channel became wider and shallower through time (also shown by periodic cross-sectional surveys). Large gravel bars have low shear stresses above them and high shear stresses around them, perhaps caused by flow accelerating around the barrier. Most important, high shear stresses are found in areas of bank erosion, and the high stresses can be maintained over a shallower cross section. Thus, the ability of the channel to transport sediment is increased under the new channel configuration.

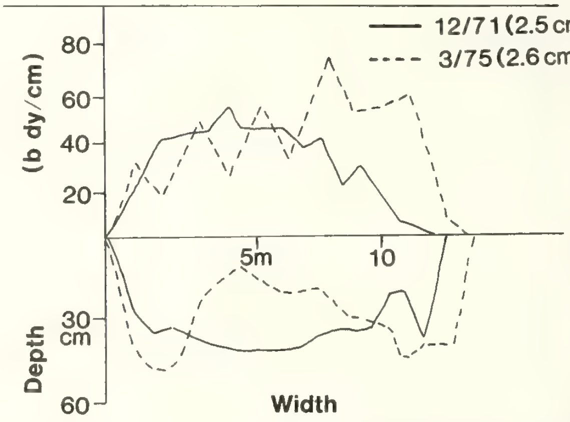

Figure 4.--Distribution of boundary shear stress in main channel, 1.6 km above the mouth of Big Beef Creek.

Channel Changes: Possible Modifications

The geometry of alluvial rivers can adjust to changing conditions imposed upon them (Mackin 1948, Leopold and Maddock 1953). In Big Beef Creek, an increase in sediment load was accommodated by changes in several interrelated hydraulic variables. Grain size and lithology of sediment supplied to a stream are variables independent of the stream system, as is discharge entering a stream. Other factors are semidependent and can undergo some modification by a stream in response to changes, i.e., flow resistance, mode of sediment transport, sediment-particle size, and channel pattern. Some parameters are almost totally functions of processes of the stream itself and can be considered to be dependent: velocity, width, depth, and channel gradient.

In response to an increase in sediment load, the more dynamic factors in a stream change to accommodate the increase. Adjustments are limited by certain physical relationships, however. The first of these is the continuity equation:

$$Q = w\,\bar{d}\,\bar{u} \qquad (3)$$

where Q = discharge, w = width, $\bar{d}$ = mean depth, and $\bar{u}$ = mean velocity.

The Manning equation (4) defines the relationship between $\bar{u}$ and $\bar{d}$:

$$\bar{u} = \frac{d^{2/3}s^{1/2}}{n} \qquad (4)$$

where s = slope of the stream-energy line and n = turbulent-friction coefficient (roughness). In addition, sediment transport, $Q_s$, is here assumed to be dependent upon stream power:

$$Q_s \ \alpha \ w\bar{d}\bar{u}s \quad . \qquad (5)$$

The manner in which the Big Beef Creek channel changed is summarized in a previous section. Theoretically, however, these changes do not represent the only possible changes, and it is important to explain why the channel has been modified in this manner. Because transport of sediment represents work accomplished, the amount of sediment transport was used as the criterion for capacity for work among various channel configurations. The Einstein method was used to compare the transport capability of several channel configurations.

Several combinations of width, depth, and velocity (restricted by continuity and roughness relationships) were tested with the Einstein computer program (fig. 5). An increase in width/depth ratio indicates increased bedload sediment transport (Schumm 1968, Pickup 1976). This holds true if velocity is held constant (line A in fig. 5), implying a decreasing roughness coefficient.

In a second set of calculations, velocity changed. If slope and roughness are considered to be a constant, k, the value of velocity from the Manning equation is $kd^{2/3}$, and discharge is defined as: $Q = kwd^{5/3}$. In this case (line B in fig. 5), rates of sediment transport decrease with increasing width/depth ratio. Therefore a change in the roughness 'n' apparently is needed to increase transport rates.

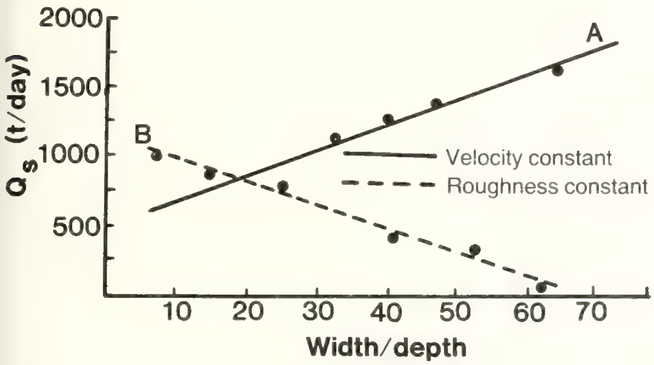

Figure 5.--Rates of sediment transport at various width-to-depth ratios.

Discharge measurements indicate that bankfull velocity remained about constant over the last 8 years, although the width-to-depth ratio, w/d, increased from 19 to 27. Line A in figure 5 suggests that w/d can increase indefinitely to transport increasingly larger sediment loads; however, in reality, stream width does not increase indefinitely. To understand what mechanism limits the increase and where these limits may be expected to occur, the effect of bed-particle roughness on flow must be considered.

Coarse surficial particles on a river-channel bed cause turbulence and energy loss in water flowing over them. The effect of these particles is most pronounced at low flows. Leopold et al. (1964, p. 160) described this phenomenon in gravel-bedded streams using a ratio of depth of water (d) to particle size ($D_{84}$) of the armor layer. The relationship is described as:

$$n_p = d^{1/6} \left[8g \left(2 \log d/D_{84} + 1.0\right)^2\right]^{-1/2} \qquad (6)$$

where $n_p$ is roughness from bed particles and g is the acceleration from gravity, 980 cm/second$^2$.

Hence roughness from bed particles is dependent only on depth of water and not on width or velocity. Values of n predicted by this method are minimum values, because other forms of roughness such as gravel bars, log jams, bank roughness, and meanders increase n. But water cannot flow over a rough bed with values of n below that predicted by the $d/D_{84}$ relationship (equation 6).

At any given discharge, if width and depth are defined, velocity is known through the continuity equation. If velocity and slope remain constant as depth changes, roughness as defined by the Manning equation must change. Figure 6 shows the relationships of width, depth, velocity, and roughness at bankfull discharge (10 m$^3$/second) in Big Beef Creek. Because no streams in the regional survey show a w/d less than 18, only those greater than 18 are considered. Actual ratios are below 27, but hypothetical cases with higher ratios are considered as well. Because survey measurements show little change in channel gradient, gradient is assumed constant in this analysis. Manning's definition represents total roughness, $n_t$, contributed by several factors; the value of $n_t$ decreases with increasing width and is given for each location considered.

With decreasing depth, roughness from bed particles, $n_p$, increases (from equation 6), and horizontal contours of figure 6 indicate the value of $n_p$ at different depths of flow.

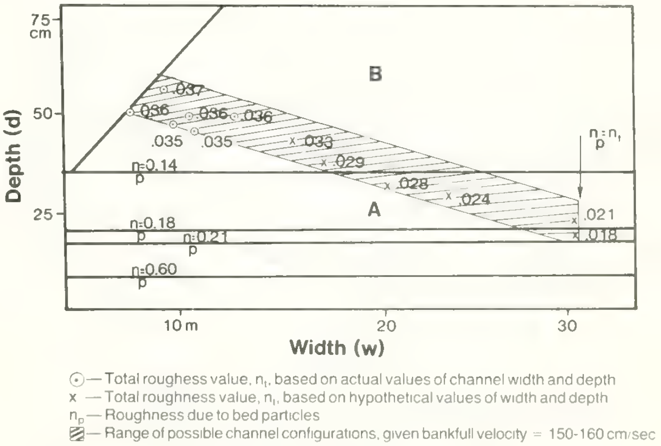

Figure 6.--Velocity and roughness constraints on the Big Beef Creek channel configuration at bankfull discharge (relationships determined from equations 3, 4, and 6).

Records from the U.S. Geological Survey gaging station show that mean velocity at bankfull stage remained between 150 and 160 cm/second over an 8-year period. Only a small portion of the diagram represents channel configurations where bankfull discharge is accommodated within this velocity range (the stippled area of fig. 6). Because velocity remained constant despite changes in channel form, I assumed velocity would remain constant if the width/depth ratio increased, and so the stippled area also includes hypothetical configurations.

As long as discharge can flow with a roughness term greater than that predicted by the $d/D_{84}$ relationship, the channel configuration is possible. Conversely, once bed-particle roughness is greater than the roughness needed to keep velocity constant, satisfying conditions of continuity, $Q = wdu$, becomes impossible. Thus, a hydraulic constraint prevents unlimited increases in channel width.

This relationship implies that the amount of sediment that can be transported as bedload is limited. Sediment transport can increase with width-to-depth ratio only as long as roughness-velocity constraints are met. If all sediment supplied to the channel cannot be transported at the maximum possible width/depth configuration, aggradation occurs.

Configurations that are not within the constant velocity envelope probably do not exist, because the amount of work necessary to create those situations is large. For example, point A in figure 4 is associated with a velocity of 213 cm/second, and $n_t = 0.0195$. Such a low value for total channel roughness is rarely, if ever, found in gravel-bedded streams (Barnes 1967). Alternately, point B in figure 4 represents a situation where velocity is 76 cm/second and $n_t = 0.087$. Because $n_p$ is only 0.008 at this depth, the $n_t$ value of 0.087 would be difficult to reach even with the contribution of other causes of roughness, and this configuration is improbable.

Big Beef Creek does not display the maximum theoretical width of 30 m. Several reasons may account for this. A stable channel must have boundaries that can withstand shear stresses imposed by the flow. Using Graf's method (1971), critical shear stress on channel walls in Big Beef Creek is between 55 and 150 dy/cm$^2$, above which erosion occurs. These stresses are approached and probably exceeded at high flows (fig. 4); however, the resistance of banks caused by vegetation must be considered. A cover of Bermuda grass can resist stresses up to 480 dy/cm$^2$ (Leopold et al. 1964). The thick mat of tree and grass roots on the banks of Big Beef Creek probably inhibits bank erosion.

Undercutting of banks below the root zone does occur, but not rapidly. The channel at the U.S. Geological Survey gaging station underwent the largest changes in 1973-74, when discharges were in excess of 20 m$^3$/second. Maximum discharge since that time has been 13 m$^3$ second. More widening may occur when another high discharge is reached, but it seems unlikely under present vegetation and discharge conditions that the channel will erode 15 m to reach 30 m.

The valley widens near the mouth of Big Beef Creek, and channel width does reach 30 m, but this partly reflects weir and tidal action effects on channel geometry.

## Storage of Sediment in the Channel

In several surveyed as well as unsurveyed reaches, much sediment eroded from roads and recently harvested hillslopes is obviously stored in the channel in the form of gravel bars. Field mapping indicates that the total volume of stored channel material is about 520 000 m$^3$ (1 092 000 t), of which 23 400 m$^3$ (49 200 t) is active material (i.e., in unvegetated bars down to a scour depth of 0.4 m) (table 2). Most active material lies in the lower 6.5 km, where channel braiding and log jams are prevalent.

An estimate of potential residence time for active material under present conditions is obtained by dividing the amount by the bedload-transport rate after disturbance, 1000 t/year, or 50 years. An average rate of movement can be estimated by dividing channel length, 10.3 km, by 50 years, or 206 m/year. Milhous (1975) obtained a particle-transport rate of 234 m/year through bedload measurements in an undisturbed, steeper channel with coarser gravel.

## Relation of Channel Changes to Land Use

Changes in the Big Beef Creek channel can be related to land use in the drainage basin. Intense logging in the mid-1950's 2000 m above the mouth dramatically increased sediment load in that reach, and aggradation occurred. Assuming bed material moves 200 m/year, effects of excess sediment would be felt near the mouth in (2000 m)/(200 m per year), or 10 years, about 1965. In fact, local residents noted excessive sedimentation in the winters of 1966-68.

Present cross-sectional surveys show degradation in the logged reach and aggradation near the mouth, suggesting the slug of sediment is being transported downstream. A high bedload rate in this reach is also indicated by field observations. Channel length decreased, and the number and size of midchannel bars increased.

A similar trend is seen 6.2 km upstream (fig. 2C). Road construction and logging in the late 1960's caused aggradation of the adjacent stream channel. Presently, net degradation is occurring there, and channel widening and braiding occur downstream for 0.8 km. This accumulation constitutes a second distinct wave of sediment in Big Beef Creek, and it will affect the stream for several years to come.

## CONCLUSION

In forested drainage basins, sediment is supplied to stream channels by soil creep and mass movements. Channel form is adjusted to the amount of sediment supplied. Logging, road construction, and urban development remove vegetation, disrupt the ground surface, and cause accelerated erosion from sheetwash, mass movements, and rainsplash erosion, and hence increase the sediment load. Under undisturbed conditions, Big Beef Creek received 500 t of sediment per year. Land-use changes increased the load to 4200 t/year. Construction of a weir at the mouth of the stream caused the bedload fraction to be caught above the weir, where an average of 1400 t of sand and gravel are deposited annually.

Stream-channel dimensions changed in response to increased sediment load. The channel in 1978 was wider and shallower than the 1970 channel, more gravel bars were present, and sinuosity decreased slightly in areas of high sediment transport. Mean flow velocity remained about constant. The changes result in an increase in shear stress along bed and banks, which in turn results in a higher rate of sediment transport. Before disturbance, sediment-transport rate of bedload was probably 300-600 t/year; at present, it is 600-1400 t/year.

Channel adaptations are restricted by hydraulic constraints described in the continuity and Manning equations. Velocity and slope are relatively conservative parameters, and most change is accommodated by width and depth.

The stream channel presently has about 1 000 000 t of sediment in storage. Active sediment, 49 000 t, moves an average of 200 m/year in the main channel. Thus sediment placed in the channel by present disturbances will take on the order of 20 to 40 years to be removed.

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# Upland Sediment Yield and Shoreline Sediment Delivery in Coastal Southern California

Brent D. Taylor

## EXTENDED ABSTRACT

In coastal southern California (fig. 1), the natural sediment system involves the continual relocation of surface geologic materials. Surface materials are eroded hydraulically from inland areas with sufficient relief and precipitation and then deposited on low-gradient coastal plains and at the shoreline where the velocity of surface runoff decreases. Generally, coarse sand, gravel, and larger particles are deposited near the base of the mountains and hills on alluvial fans, and finer sediments are deposited further downstream on floodplains, in bays or lagoons, and along the shoreline. Very fine silt and clay particles, which make up a significant part of the eroded material, are carried offshore where they eventually accumulate in deeper areas. Finally, sand delivered to the shoreline is moved along the coast by waves and currents until it is lost to offshore areas through submarine canyons and other paths.

Human developments in this region have substantially altered the natural sediment-transport system--through timber harvest, grazing, and sand and gravel mining; the construction and operation of water conservation facilities and flood-control structures; and shoreline developments.

Almost always, these developments have grown out of recognized needs and have served their primary purposes well. Possible deleterious effects on the local or regional sediment balance were initially unforeseen or felt to be of secondary importance.

Since 1975, the Environmental Quality Laboratory (EQL) at the California Institute of Technology and the Shore Processes Laboratory at Scripps Institute of Oceanography have conducted a joint study to define quantitatively:

- The natural system of inland and coastal transport of sediment in southern California.

- The extent to which human activities have altered this natural system.

A comprehensive EQL report, currently being prepared, is scheduled for publication during 1981 and will be available for general distribution.[1/]

Inland areas can be identified as either erosional or depositional according to recent geological activity. Erosional areas have been subdivided into drainage basins, and estimates of average annual sediment yield have been computed based on

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Brent D. Taylor, Senior Research Engineer, Environmental Quality Laboratory, California Institute of Technology, Pasadena, California 91125.

[1] Sediment Management for Southern California Mountains, Coastal Plains and Shoreline, Environ. Qual. Lab. Rep. No. 17, Calif. Inst. Technol. 1981, 100 p. 17-A: Regional geological history, Edward W. Fall, 1981, 30 p., 4 maps; 17-B: Inland sediment movements by natural processes, Brent D. Taylor, 1981, 100 p., 2 maps; 17-C: Coastal sediment delivery by major rivers in southern California, William R. Brownlie and Brent D. Taylor, 1981, 292 p.; 17-D: Special inland studies, William W. Brown III, Oded C. Kolker, Nancy Palmer, Wade Wells, 1981, 150 p., 4 maps; 17-E: Shoreline sedimentation processes, Douglas L. Inman, Abraham Golick, and Martha Shaw, Scripps Inst. Ocenogr., 1981, 250 p.; 17-F: Special coastal studies, Martha Shaw, Scripps Inst. Oceanogr., 1981, 150 p., 2 maps.

debris-accumulation data from 36 entrapment structures located in the study area and a simple regression model relating sediment yeild to dominant land type and drainage-basin areas.

Measured denudation rates vary from about 0.01 mm/year on plains areas to 3 to 5 mm/year in small, mountainout drainage basins. Denudation rates for each land type are remarkably uniform throughout the study area despite significant variations in rock types, geological history, and the size distribution of eroded materials.

Study results indicate that in these coastal drainage basins, an average of more than 12 million $m^3$ of sediment leave upland drainage basins each year. This material (6 million $m^3$ fines, 5 million $m^3$ sand, and 1 million $m^3$ of coarser material) is first delivered to inland valleys, coastal plains, or directly to the shoreline--depending on drainage-basin location.

Estimates have also been obtained for average annual sediment delivery to coastal areas from each of the larger hydrographic drainage units (fig. 1, table 1). Specific effects on upland erosion and shoreline sediment delivery of human developments and artificial control structures are also determined. Available data indicate that while upland erosion on 10 major rivers that drain 64 percent of the 31 000-$km^2$ coastal area has been altered very little, shoreline sediment delivery of beach-sized sand from these rivers has been reduced some 50 percent over the past 50 years.

Comparisons of sediment yield from upland drainage basins with coastal delivery by major rivers suggest that, under natural conditions, alluvial rivers in the southern part of the study area are depositional along their floodplains, with only a fraction of upland sediment production being delivered to the shoreline. The three northern rivers, on the other hand, are erosional on their floodplains and deliver more sediment to the shoreline than is yielded from their respective upland basins.

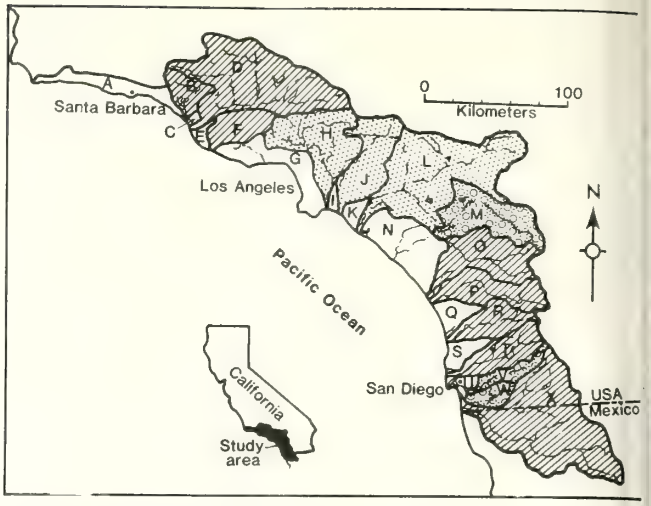

Figure 1.--Coastal southern California hydrographic drainage units identified in table 1.

Table 1--Major drainage units in the sediment-management study area

| Map symbol | Principal basin or group of small basins | Basin type | Controlled drainage area | Total drainage area | Percent of drainage area controlled |
|---|---|---|---|---|---|
| | | | - - - Square kilometers | - - - | |
| A | Santa Ynez Mountains Group | G | -- | 901 | -- |
| B | Ventura River Basin | SMD | 243 | 585 | 42 |
| C | Ventura Group | G | -- | 52 | -- |
| D | Santa Clara River Basin | SMD | 1 527 | 4 219 | 37 |
| E | Oxnard Group | G | -- | 159 | -- |
| F | Calleguas Creek Basin | SMD | -- | 837 | -- |
| G | Santa Monica Mountains Group | G | 166 | 1 493 | 11 |
| H | Los Angeles River Basin | SED | [3]866 | 2 155 | 40 |
| I | Long Beach Group | G | -- | 120 | -- |
| J | San Gabriel River Basin | SED | 1 400 | 1 663 | 84 |
| K | Huntington Beach Group | G | -- | 234 | -- |
| L | Santa Ana River Basin | SED | 3 950 | 4 406 | 90 |
| M | Lake Elsinore Basin | SC | 1 989 | 1 989 | 100 |
| N | Laguna Hills Group | G | -- | 1 737 | -- |
| O | Santa Margarita River Basin | SMD | 958 | 1 927 | 50 |
| P | San Luis Rey River Basin | SMD | 531 | 1 450 | 37 |
| Q | Escondido Creek Group | G | -- | 568 | -- |
| R | San Dieguito River Basin | SMD | 785 | 896 | 88 |
| S | San Clemente Canyon Group | G | -- | 437 | -- |
| T | San Diego River Basin | SMD | 686 | 1 119 | 61 |
| U | San Diego Group | G | -- | 157 | -- |
| V | Sweetwater River Basin | SC | 471 | 567 | 83 |
| W | Otay River Basin | SC | 255 | 370 | 69 |
| X | Tijuana River Basin | SMD | 3 175 | 4 483 | 72 |
| Total | | | 17 002 | 32 524 | 53 |

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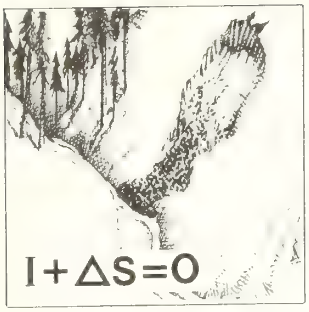
[1] G, drainage basin group; SED, single, extensively developed basin; SC, single confined basin; SMD, single, moderately developed basin.

[2] Calculated by adding the drainage areas controlled by the major water-retention structures that are farthest downstream in each basin.

[3] Whittier Narrows Flood Control Basin controls both Los Angeles and San Gabriel Rivers. This estimate assumes that 35 $km^2$ of the drainage area controlled by the Whittier Narrows structure lies within the Los Angeles River drainage basin.

[4] Excludes Lake Elsinor Basin (M).

[5] Closed interior basin. Overflow into Santa Ana River basin has not occurred since 1916.



# Ashland Creek Drainage Basin Sediment Budgets and Routing Studies

Richard D. Smith and Bill G. Hicks

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Richard D. Smith, Geologist; Bill G. Hicks, Engineering Geologist, Rogue River National Forest, Medford, Oregon 97501.

## EXTENDED ABSTRACT

The Ashland Creek drainage basin which supplies water to the city of Ashland, Oregon, has experienced major problems with erosion and landslides. Debris avalanches, originating in weathered granitic rock, have moved down the major drainages, damaging the water-supply system and partially filling the water-supply reservoir.

Two studies to develop partial sediment budgets have been conducted to assess the relative effects of natural and management-related sediment production. The first was completed by the Rogue River National Forest[1] in 1975 and specifically dealt with the material deposited in Reeder Reservoir at the base of the 5020-ha drainage basin by a major storm in January 1974. The second study was completed in 1977 by J. M. Montgomery Consulting Engineers,[2] Boise, Idaho. This study, prepared for the City of Ashland, was initiated because of the 1974 storm, but included an analysis of sediment production in the Ashland Creek drainage for the period 1955-76.

At the time of the January 1974 storm, 85 km of road had been constructed in the basin, covering about 90 ha or 2 percent of the area including cut and fill slopes. Clearcutting and partial cutting had occurred in 7 percent of the basin and another 1 percent had been thinned.

The USDA Forest Service study included mapping of all failures in the basin, subdividing them into management-related and natural events. Rough estimates were made of failure volumes released into the system. These volumes were then compared with the volume deposited in the reservoir during the storm event. The difference between the landslide failure volume and volume collected in the reservoir was then subdivided into stream-channel erosion of natural and management-related, pre-1974 material in channels. Estimates of surface erosion from roads were about equal to the estimated natural surface erosion for the 1974 storm. Additional assumptions and interpretations were made to arrive at comparative estimates of management-related and natural sources of material deposited in the reservoir (table 1). About 60 percent of the material in the reservoir was attributed to management-related activities and 40 percent to natural events.

The Montgomery study covered the full range of erosional factors in the basin. It developed a simulated history of sediment production for the entire Ashland Creek drainage. To approximate erosion rates related to roads and timber harvest, data from granitic terrane of the Idaho batholith were used. Significant volumes were attributed to road-related erosion, including effects of annual road maintenance. The study stressed that the technique used analyzes only surface and mass erosion for the entire drainage basin. The data and conclusions do not deal with routing through the drainage system to the reservoir. The approach was designed to approximate sediment supply to channels in response to various management activities within the drainage basin. This portion of the Montgomery study highlights the various factors affecting the total erosion rate and thus forms a basis for making decisions on where to intensify field investigations. The study identifies the sources of an estimated 270 000 $m^3$ of soil erosion from 1955 to 1977: natural (3 percent), surface erosion from 1- to 2-year-old road surfaces (6 percent), surface erosion from older road surfaces (58 percent), surface erosion from cut and fill slopes of roads (1 percent), mass movement from roads and timber harvest sites (20 percent), surface erosion from timber-harvest units (3 percent), and surface erosion from ski areas (9 percent).

Contrasts between the two studies result from the use of different data bases, recognition of channel-sediment sources in the Forest Service study and not in the Montgomery study, and differences in the time period analyzed.

Table 1--Estimates of sediment derived from various sources in Ashland Creek drainage basin[1/]

| Source | Volume |
|---|---|
| | Cubic meters |
| Management-related: | |
| Mass failure of road fills | 21 700 |
| Other mass failures from roads | 6 200 |
| Mass failures from clearcuttings | 150 |
| Stream-channel erosion (debris-slide effect) | 15 300 |
| Management-related, pre-1974 material in channels | 15 300 |
| Management-related subtotal | 58 650 |
| Natural: | |
| Stream-channel erosion (major storm-flow effect) | 35 600 |
| Stream-channel erosion (debris-slide effect) | 1 700 |
| Debris slides | 3 600 |
| Natural subtotal | 40 900 |
| Total sediment delivery to reservoir | 99 550 |

[1/] See text footnote 1.

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[1] Wilson, S., and B. G. Hicks. 1975. Slope stability and mass wasting in the Ashland Creek watershed. Unpubl. rep., on file Rogue River Natl. For., Medford, Oreg.

[2] J. M. Montgomery Consulting Engineers. 1977. Water resources management plan and facility study. Unpubl. rep., on file Rogue River Natl. For., Medford, Oreg.

# Channel Sediment Storage Behind Obstructions in Forested Drainage Basins Draining the Granitic Bedrock of the Idaho Batholith

Walter F. Megahan

## ABSTRACT

Data on sediment storage behind obstructions were collected on seven forested, mountain drainage basins in the Idaho Batholith for a 6-year period from 1973-78. Four of the drainage basins were undisturbed throughout the study period, one contained an old road, and two were logged during the course of the study. The total volume of sediment stored behind obstructions varied between drainage basins and years in response to changes in bankfull channel width and annual peak-flow rates, respectively. Logs were the most important type of obstruction because they had the greatest longevity and stored the greatest amount of sediment. An average of 15 times more sediment was stored behind obstructions than was delivered to the mouths of the drainages as annual average sediment yield. Logging reduced total channel-sediment storage behind obstructions because many natural obstructions were destroyed by felling and subsequent clearing operations to remove logging debris from channels. Storage behind obstructions is an important component of the overall sediment routing through forested drainage basins. Accordingly, erosion and sedimentation monitoring must be carefully designed to avoid misinterpretation. Also, some guidelines are presented to help minimize the change in channel-sediment storage caused by timber harvest.

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Walter F. Megahan, Principal Research Hydrologist,
Forestry Sciences Laboratory, 316 East Myrtle
Street, Boise, ID 83702.

## INTRODUCTION

Development of a sediment budget for a drainage basin requires an accounting of: (1) onsite erosion; (2) the amount and rate of transport of eroded material between source and stream channels; (3) channel-sediment storage; and (4) sediment outflow from the basin. Channel-sediment storage is especially important on forested drainage basins because of additional storage potential provided by obstructions. Obstructions from logs and other debris occur naturally on forested areas, but their size and abundance may be strongly influenced by stand conditions and by disturbances such as logging (Froehlich 1973, Swanson et al. 1976, Swanson and Lienkaemper 1978).

Information on the volume of sediment storage and the type, size, number, and longevity of the obstructions causing the storage is needed to provide better understanding of channel-storage processes in forested drainage basins. Megahan and Nowlin (1976) reported on a study of sediment storage in channels draining seven small forested drainage basins in the mountains of central Idaho. Part of that study included an inventory of sediment trapped behind obstructions in 1973-74. This paper summarizes the progress made through 1978 in the channel obstruction portions of the study.

## DESCRIPTION OF THE STUDY AREA

The seven drainage basins are in the Silver Creek study area in the Middle Fork of the Payette River drainage near Crouch, Idaho.

Descriptive data for the study drainage basins are presented in table 1. Four of the seven study drainage basins are undisturbed; the Ditch Creek drainage contains a low-standard road constructed during the 1930's and Control and K-1 Creeks were logged by helicopter in November 1976. The forest cover is dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Laws.) on the slopes and grades into grand fir (*Abies grandis* [Dougl.] Forbes) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) near drainage bottoms. Timber volumes average about 117 $m^3$/ha in the vicinity of drainage bottoms.

The area is representative of conditions in the Idaho Batholith, a 41 400-$km^2$ expanse of granitic bedrock in central Idaho (fig. 1). This mountainous area is characterized by steep slopes; shallow, extremely erodible, coarse-textured soils; and large climatic events resulting from rainfall, snowmelt, or both. Erosion hazards are high and soil disturbances, both natural and caused by human activities, can greatly accelerate erosion and consequent sedimentation (Megahan 1975). Much of the total sediment discharge occurs as bedload, because of the coarse texture of the granitic parent materials. Streamflow and sediment yield exhibit marked seasonal variation in response to large winter storms, spring snowmelt, and long, dry periods in summer.

## METHODS

Data on sediment storage behind obstructions were collected at sample reaches in each study drainage basin. Each sample reach is 43 m long. The first sample reach is located 30 m above a sediment basin at the mouth of each drainage. Additional sample reaches are located at 152-m intervals along the dominant channel until no indicators of perennial streamflow are obvious (such as a well-defined channel cross section or aquatic vegetation). The dominant channel was defined by following the mainstream up from the drainage-basin outlet during the period of baseflow in August and selecting the tributary with the greatest flow at each confluence.

Table 1--Descriptive data for seven drainage basins on the Silver Creek study area

| Drainage | Area | Mid-elevation[1] | Dominant aspect | Mean channel gradient[2] | Total channel length[3] | Stream order[3] | Average bankfull width |
|---|---|---|---|---|---|---|---|
| | Sq. kilometers | Meters | | Percent | Kilometers | | Meters |
| C | 1.94 | 1779 | SE | 21.5 | 9.5 | 3 | 1.5 |
| D | 1.22 | 1765 | SE | 24.2 | 5.5 | 2 | 1.1 |
| Eggers | 1.29 | 1733 | SE | 22.0 | 5.8 | 3 | 1.1 |
| Ditch | 1.06 | 1631 | SE | 20.8 | 2.9 | 2 | 0.8 |
| Cabin | 1.04 | 1533 | SE | 14.9 | 5.1 | 3 | 1.0 |
| Control | 2.02 | 1597 | SE | 15.2 | 6.8 | 3 | 1.1 |
| K-1 | 0.26 | 1623 | NW | 31.5 | 1.0 | 1 | 1.0 |
| Average | 1.27 | 1666 | -- | 21.4 | 5.1 | -- | 1.1 |

[1] (Maximum elevation + minimum elevation)/2.

[2] (Total relief/length main channel to the upper ridge) x 100.

[3] Taken from a 1:31,680 planimetric map.

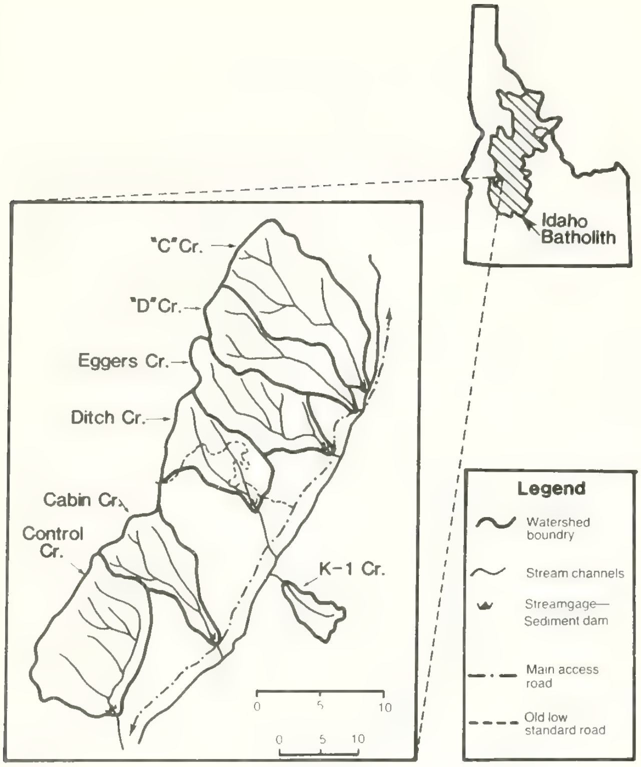

Figure 1.--Study area in the Idaho Batholith.

An average of 10 reaches was sampled on each study channel for an average of 27 percent of the study channel sampled. Because sample reaches are located only on the dominant channel in each drainage basin, only about 8.7 percent of the total channel length in each drainage basin is sampled (table 2). Data are collected annually during low flow in late July and August. All reaches on all streams were sampled only during 1973, 1974, and 1978. In 1975, all samples were taken except the upper four reaches on C Creek. C, D, Eggers, Ditch, and Cabin Creeks were not sampled in 1976; C and D were omitted again in 1977.

Data for sediment deposited behind obstructions are available for 1973-78. Obstructions are defined as any material in the channel causing sediment accumulations because of discontinuities in channel gradient. In 1973, all discernible obstructions and associated sediment accumulations were measured, a procedure that proved to be too time consuming. Sampling during the following years was restricted to obstructions with the following minimum dimensions: height, 0.2 m; average width, 0.3 m; and length, 0.6 m. The effect of the more restrictive sampling is minimal; 31 percent of the total number of obstructions fell below the allowable limit in 1973 but accounted for only 11 percent of the total volume of stored sediment. Height is defined as the difference between a level rod reading taken on the bed at the downstream side of the obstruction (the rod is raised if necessary to correct for any scouring at this point) and a rod reading taken on the sediment deposit immediately upstream from the obstruction. Rod readings are taken to the nearest 0.4 cm using an abney level. Length is the distance from the upstream end of the obstruction to the upstream end of the accumulated sediment. Width of the sediment accumulation is the average of 3 widths taken normal to the length at distances of 0.17, 0.5, and 0.83 of the length from the obstruction. The upstream end and edges of sediment accumulations are defined by breaks in channel gradient, differences in the particle-size distribution of bottom sediments, and differences in composition of bottom materials. A third rod reading is taken at the upstream end of the accumulated sediment to allow calculation of the slope of the deposited sediments. The most apparent cause of the obstruction is defined by type, as log (woody material over 10 cm in diameter), rock, root, stump, or debris, which includes branches, twigs, and leaves. Finally, the location of the obstruction is mapped.

A continuously recording streamgage and a sediment basin for determining annual sediment yields are operated at the mouth of each drainage basin. Sediment basins are surveyed twice a year in June and October using a network of closely spaced

Table 2--Sampling intensity on study drainage basins

| Drainage | Number of sample reaches | Length of study channel | Percent of study channel sampled for obstructions | Percent of total channel length sampled for obstructions |
|---|---|---|---|---|
| | | Meters | | |
| C | 14 | 2198 | 27.2 | 6.3 |
| D | 8 | 1210 | 28.2 | 6.2 |
| Eggers | 12 | 1868 | 27.4 | 8.8 |
| Ditch | 11 | 1704 | 27.5 | 16.1 |
| Cabin | 9 | 1539 | 25.0 | 7.4 |
| Control | 11 | 1704 | 27.5 | 6.9 |
| K-1 | 4 | 552 | 30.9 | 17.7 |
| Average | 9.9 | 1539 | 27.3 | 8.7 |

Table 3--Average number of obstructions and volume of sediment stored behind obstructions in study streams per 30 m of channel sampled

| Year | C | D | Eggers | Ditch | Cabin | Control[1] | K-1[1] | Mean |
|---|---|---|---|---|---|---|---|---|
| | Number/volume cubic meters | | | | | | | |
| 1973 | 4.5<br>2.3 | 6.2<br>2.3 | 3.2<br>0.6 | 3.9<br>0.7 | 3.9<br>0.7 | 2.8<br>0.4 | 3.6<br>0.7 | 4.0<br>1.1 |
| 1974 | 3.1<br>1.9 | 3.6<br>1.6 | 2.4<br>0.5 | 3.1<br>0.8 | 2.8<br>0.7 | 2.8<br>0.6 | 4.3<br>1.2 | 3.0<br>1.0 |
| 1975 | 2.2<br>1.4 | 3.4<br>1.1 | 2.6<br>0.4 | 3.7<br>0.4 | 3.4<br>0.5 | 2.7<br>0.6 | 4.5<br>0.5 | 3.1<br>0.7 |
| 1976 | --<br>-- | --<br>-- | --<br>-- | --<br>-- | --<br>-- | 4.2<br>1.0 | 7.5<br>0.9 | 4.9<br>0.9 |
| 1977 | --<br>-- | --<br>-- | 3.9<br>0.4 | 4.4<br>0.5 | 4.9<br>0.7 | 2.4<br>0.3 | 4.6<br>0.6 | 3.9<br>0.5 |
| 1978 | 3.6<br>1.4 | 4.4<br>0.6 | 3.5<br>0.2 | 3.4<br>0.4 | 5.8<br>0.4 | 3.8<br>0.6 | 5.9<br>0.7 | 4.1<br>0.6 |
| Mean | 3.1<br>1.8 | 4.4<br>1.4 | 2.9<br>0.4 | 3.5<br>0.6 | 4.0<br>0.6 | 3.0<br>0.5 | 5.0<br>0.8 | 3.6<br>0.8 |

[1] Drainage basins logged in November 1976.

cross sections. Generally, more than 95 percent of the total sediment yield for the year is measured during the June survey. Trap efficiencies of the basins are estimated to average more than 75 percent because of the coarse texture of the soils on the study drainage basins (Megahan 1975). Two weather stations and a raingage network are also operated on the study area.

## RESULTS AND DISCUSSION

A total of 1,715 obstructions were sampled during the 6 years of data collection. Averaging all years and streams, 3.6 obstructions were found per 30 m of channel with 0.8 $m^3$ of sediment storage per obstruction. This amounts to 2.9 $m^3$ of sediment storage per 30 m of channel or 493 $m^3$ for the average total channel length on the study drainage basins.

### Number of Obstructions and Sediment Storage

As might be expected, the number of obstructions and stored sediment volumes vary between streams and between years (table 3). Analysis of variance tests show significant ($\alpha = 0.01$) differences between streams for both number of obstructions and volume of stored sediment.

Heede (1972) reported an increase in number of obstructions with increasing channel gradient on two study streams in Colorado. A similar analysis proved unsuccessful for the streams in this study. Reasons for the lack of agreement are not clear, although the fact that the Idaho streams are smaller and steeper is probably a contributing factor. As with number of obstructions, volume of sediment stored behind obstructions was not related to channel gradient. Average volume of sediment ($m^3$) behind obstructions showed a weak, positive relationship to average bankfull channel width (m), however. A linear regression analysis had a coefficient of determination of 0.62 and a standard error of 0.3 $m^3$/30 m. The regression coefficient was 0.526 (significant at the 0.05 level) and the y intercept was -0.54 m. Other, presently unexplored, factors--such as quality, type, and condition of streamside vegetation--would likely provide better predictors of number of obstructions and sediment storage behind obstructions.

Assuming no major changes in the factors introducing obstructions to the channel (such as windstorms), variations in streamflow probably account for some of the annual changes in number of obstructions and sediment storage behind obstructions. This is illustrated by comparing the frequency distribution of sediment stored behind obstructions for years of high and low flow (fig. 2). During the high-flow year of 1974, when peak flows averaged 0.20 $m^3$/sec per ha, only the large, stable obstructions remained in the channel. In contrast, more obstructions with a smaller volume were found when flow energies were low, as in 1978 when average peak flows were about half those recorded in 1974.

### Type of Obstruction

Debris was the most common type of obstruction, averaging about 42 percent of the total. Logs formed 34 percent of all obstructions; rocks, roots, and stumps made up an additional 13, 10, and 1 percent, respectively.

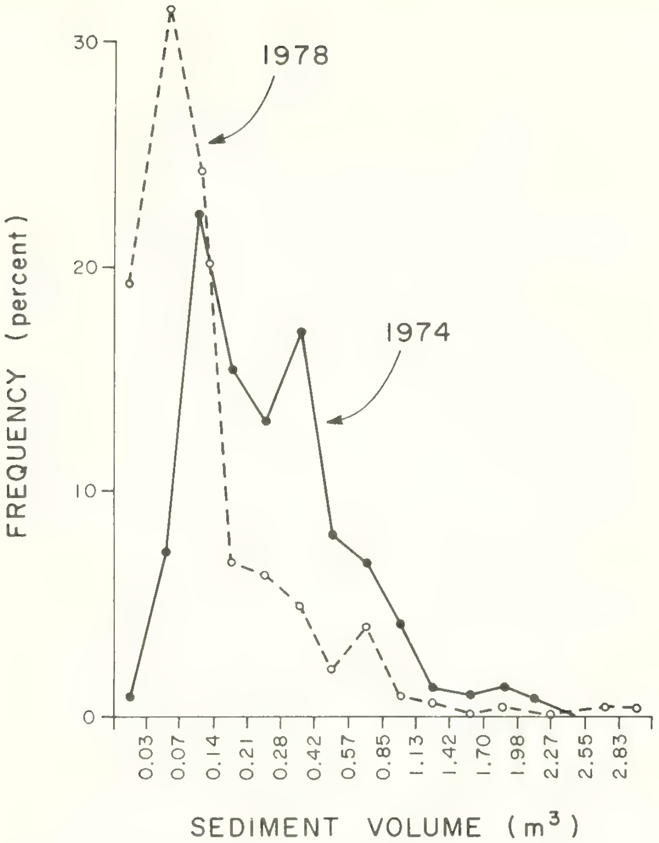

Figure 2.--Frequency of occurrence of sediment volume behind obstructions by size classes.

Because of differences in amount of stored sediment, frequency of occurrence alone does not reflect the importance of obstruction type. A comparison of the frequency of occurrence of volume of sediment storage behind the two most common types of obstructions illustrates this (fig. 3). Although fewer obstructions are logs than debris, the logs store greater amounts of sediment, which greatly magnifies the importance of logs. Logs account for 49 percent of the total sediment stored, but organic debris accounts for only 29 percent. An additional 16, 6, and 0.2 percent of the sediment storage is caused by rock, roots, and stumps.

Longevity of Obstructions

The number of obstructions in a channel at any time is a function of the rate of introduction of new obstructions to the channel from adjacent slopes, the longevity of obstructions once in place, and the rate of supply of obstruction material from upstream. Introduction of new obstructions occurs as a long-term, relatively constant supply of material from normal ecological processes in the forest--such as litterfall and random mortality--plus a stochastic component caused by natural catastrophic disturbances--such as forest fire, windstorm, and logging. Once introduced, longevity of obstructions (defined as the length of time an obstruction was found at a given location) is a function of the rate of decay of organic materials and the tendency for movement of the obstruction, erosion around it, or both. If the obstruction material moves, it then has the potential for forming a new obstruction further downstream.

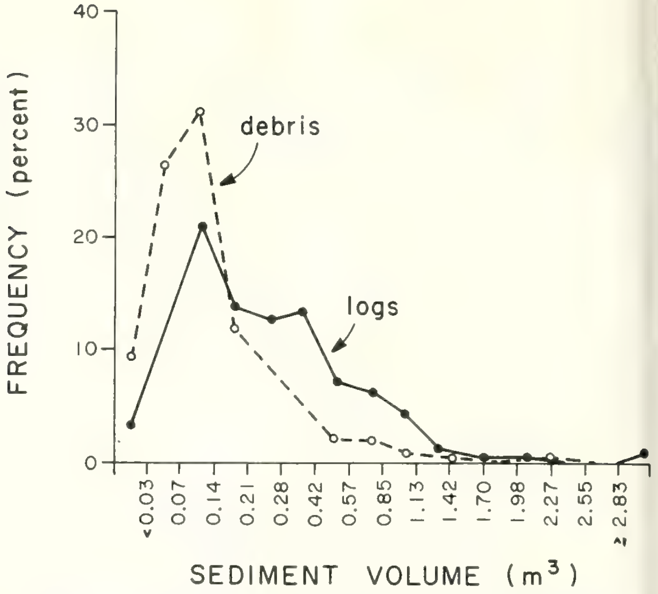

Figure 3.--Frequency of occurrence of sediment volume by size classes stored behind debris and log obstructions.

Development of a model for occurrence of obstructions is beyond the scope of the present data. Information is available to illustrate the longevity of obstructions once they have formed, however. During the field survey, the distance along the channel is measured from a permanent reference point. This makes it possible to define the longevity of obstructions by comparing data for successive years. Data are available for 6 years for Control and K-1 Creeks. The longevity of all types of obstructions tends to decrease rapidly with age, but the rate of decrease for logs is lower than for the other types (fig. 4). This further emphasizes the importance of logs as channel obstructions; they not only retain the most sediment but also last longest.

Decay is probably an important process influencing the rate of decline of debris obstructions. Decay rates are slow for logs in a wet environment, however, so erosion under and around the log (or both) is probably a more important cause for failure. Logs often serve as indirect causes of obstructions by acting as channel obstacles that do not in themselves restrict flow but rather form a base for the collection of debris that does. Then, the longevity of the obstruction depends on the longevity of the secondary material rather than the log itself, even though the obstruction is classified as a log.

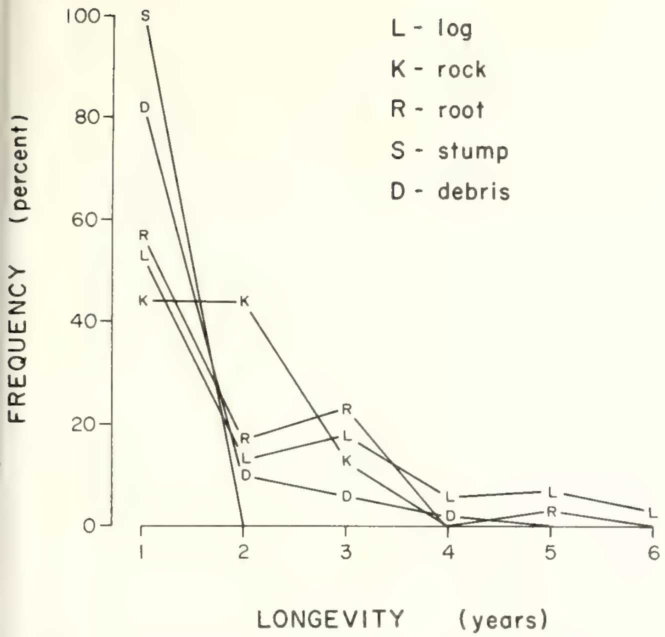

Figure 4.--Frequency of occurrence of the number of years an obstruction remains in place by obstruction type.

Volume of Sediment Storage Behind Obstructions

Channel-sediment storage is an important component of the overall sediment budget for a forested drainage basin. The three types of channel storage are: (1) temporary storage in channel bedforms as a function of flow conditions and sediment-particle size; (2) longer term storage caused by obstructions; and (3) very long-term valley storage in flood-plain deposits. The importance of storage behind obstructions is illustrated by comparing sediment storage with annual sediment yield. Annual sediment yield measured in debris basins at the mouth of each study drainage basin is much less than the average annual sediment storage for study reaches extrapolated to the total channel length (table 4). The ratio of storage to yield ranges from a high of 33 for the largest drainage (C Creek) to a low of 3.0 for Ditch Creek, and it averages 15. The ratio for Ditch Creek is much lower than that for any other drainage, because Ditch Creek contains an old, low-standard road that doubles sediment yield from the drainage basin (Megahan 1975).

Table 4--Average annual volume of sediment stored behind obstructions compared to average annual sediment yield in debris basins

| Stream | Sediment storage behind obstructions | Sediment measured in debris basin | Obstruction storage/ debris basin |
|---|---|---|---|
| | Cubic meters | | |
| C | 534 | 16 | 33 |
| D | 282 | 11 | 26 |
| Eggers | 75 | 8 | 9 |
| Ditch | 52 | 17 | 3 |
| Cabin | 101 | 11 | 9 |
| Control | 127 | 11 | 12 |
| K-1 | 24 | 3 | 8 |
| Average | 171 | 11 | 15 |

These observations emphasize the need to account for channel storage when working with sediment yields from small drainage basins in forested areas. On the average, about 15 years of annual sediment yields are stored behind obstructions. Given a large enough hydrologic event, much of this material could be flushed out of the system. Unless the previous channel storage were accounted for, this sudden increase in sediment yield might be attributed to recent onsite hillslope erosion when in fact it originated from channel-erosion processes.

Effects of Logging in the Study Drainage Basins

Control and K-1 Creeks were logged during this study. All trees down to 25 cm diameter breast high were clearcut in Control Creek on three major cutting units totaling 35 ha. The entire area of K-1 Creek was selection logged. Logs were removed from both drainage basins by helicopter. Only trees that were likely to die before the next timber harvest were marked for cutting within 15 m of active stream channels on both drainage basins. The logging contract stipulated that logging debris entering stream channels was to be removed.

The logging was done in November 1976. Channel surveys the following summer showed that logging debris had encroached on stream channels during timber harvest; in extreme cases, entire trees had rolled lengthwise into the channel. All logging slash was removed from the channel in accordance with the timber sale contract, however. Contrary to results at other locations, this logging temporarily decreased sediment storage behind obstructions, chiefly because some of the natural obstructions were destroyed by the tree felling and channel cleaning operations. This is illustrated by comparing double mass curves for the logged drainage basins to adjacent unlogged drainages (figs. 5 and 6). Although the trends shown are not statistically significant, numbers of obstructions and stored volumes tended to decrease in 1977 after logging. These results are reinforced by comparing the change in volume of sediment stored behind obstructions in a stream from one year to the next (table 5). Sediment storage decreased from 1976 to 1977 for both Control and K-1 Creeks, followed by a net increase from 1977 to 1978.

Table 5 also illustrates the need to consider all components of the sediment budget when developing drainage-basin sediment budgets. Positive and negative values in the table indicate annual increases or decreases in the total volume of sediment storage behind obstructions. A constant outflow of sediment occurs from the drainage basins each year into the sediment basins. Assuming that the figures in the table are correct, other forms of channel sediment storage and erosion processes both in the channel and on the slopes obviously must be evaluated to balance the annual sediment budget.

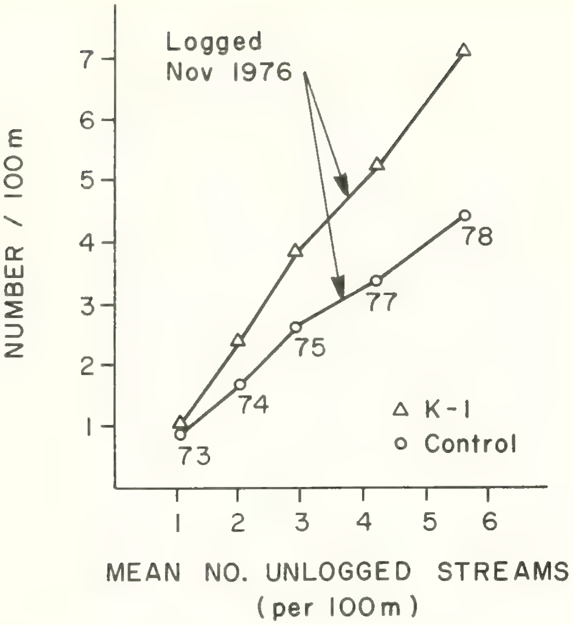

Figure 5.--Double mass analysis showing number of obstructions before and after logging.

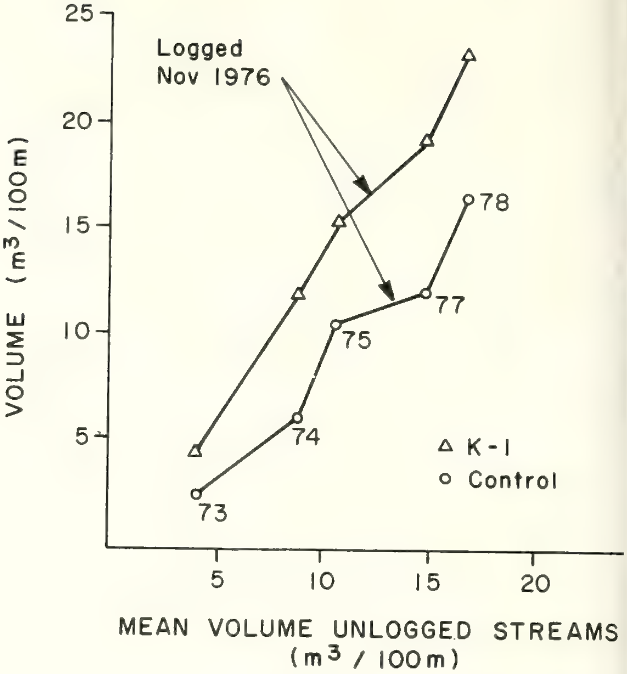

Figure 6.--Double mass analysis showing volume of sediment storage behind obstructions before and after logging.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Both numbers of obstructions and volume of sediment stored behind obstructions varied by drainage basins and by years. Differences between drainage basins were partly accounted for by a direct relationship to bankfull channel width, and differences between years were inversely related to annual instantaneous peak flow rates. Obstructions caused by organic debris were most numerous. Log obstructions were by far the most important, however, because logs store more sediment per obstruction and last longer. Longevity of obstructions is influenced by the decay rate of the material forming the obstruction and by movement of and erosion around obstructions. Most obstructions in the study area lasted less than 2 years. Even the most permanent type of obstruction, logs, lost 97 percent of their effectiveness for storing sediment within 6 years after emplacement.

Extrapolation of storage data to entire channels shows that, on the average, about 15 times more sediment is stored behind obstructions than is yielded annually at the drainage-basin mouth. This illustrates the importance of sediment storage to overall erosion-sediment budgeting for forested drainage basins.

Clearcutting and selection logging by helicopter had little effect on channel obstructions in the study area because of minimal streamside cutting and postlogging channel clearing. The net effect of logging was to cause a small decrease in the number of obstructions and in sediment stored behind obstructions for 1 year afterward.

The total amount of sediment stored behind obstructions fluctuated between years; however, sediment outflow was measured from all basins for all years. These data further emphasize the need to consider other types of channel storage, including bedforms and flood-plain storage, in addition to streambank erosion and erosion on slopes for a complete understanding of sediment budgets for forested drainage basins.

Some important land-management implications can be derived from this study for timber harvesting and methods to monitor erosion and sedimentation responses to land-management activities.

Table 5--Change in sediment stored behind obstructions in study streams

| Year | C | D | Eggers | Ditch | Cabin | Control | K-1 |
|---|---|---|---|---|---|---|---|
| | | | | Cubic meters | | | |
| 1973-74 | -129.2 | -123.9 | -14.2 | + 7.4 | + 2.4 | + 46.5 | +17.8 |
| 1974-75 | -350.9 | - 88.7 | -34.2 | -38.5 | -25.5 | + 13.1 | -21.9 |
| 1975-76 | -- | -- | -- | -- | -- | + 74.0 | +12.1 |
| 1976-77 | -- | -- | -- | -- | -- | -150.0 | -10.9 |
| 1977-78 | -- | -- | -41.2 | -13.0 | -49.5 | + 76.7 | + 1.9 |

### Timber Harvest

Timber-harvest activities should be designed to minimize changes in channel-sediment storage during and after disturbance by:

- Wherever possible, logging debris should be kept out of stream channels.

- If logging debris does get into stream channels during logging, it should be carefully removed to avoid disturbance of natural obstructions.

- An additional point to consider when evaluating the desirability of buffer strips is that they provide a source of natural channel debris that helps to stabilize channel-sediment storage over time after timber harvest.

### Monitoring Erosion and Sedimentation Effects

Monitoring erosion and sedimentation from land uses is often necessary to help minimize impacts on fish, assure compliance with water-quality standards, or because of legislation calling for monitoring of the environmental effects of land-management activities. The objectives of the monitoring effort must be carefully defined and the monitoring designed accordingly. If onslope erosion is the concern on a particular area, then erosion should be measured at that point. Similarly, downstream sediment yield should be measured at a relevant downstream point if water-quality standards or fishery impacts are important. Inferences about erosion from sediment data or about sediment from data on erosion should be made with extreme caution, unless the data are collected to evaluate the third component of the erosion-sedimentation continuity equation--sediment storage. This is particularly important in areas where a large proportion of the sediment moves as bedload.

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# Development, Maintenance, and Role of Organic-Debris Dams in New England Streams

Gene E. Likens and Robert E. Bilby

ABSTRACT

We propose that the formation of organic-debris dams on streams depends primarily on the size of tree (log) available. After disturbance, organic-debris dams are at first diminished and then form on larger and larger stream channels as the terrestrial ecosystem develops, and as a result, the regulation of erosion and transport of dissolved and particulate material from the landscape is enhanced. The species composition and phase of development of hardwood forests also may affect the occurrence and longevity of organic-debris dams. Steady-state amounts of organic matter in stream channels may reflect the stream order, as well as the developmental phase of the terrestrial ecosystem.

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Gene E. Likens, Professor of Ecology, and Robert E. Bilby, Research Associate, Section of Ecology and Systematics, Cornell University, Ithaca, New York 14850.

## NTRODUCTION

n organic-debris dam is an accumulation of rganic matter that obstructs water flow in a tream. In general, these structures form when a iece of large woody debris falls into the stream. nless the woody piece is extremely large, such as tree bole, the wood will be carried downstream ntil it reaches a point in the channel where ocks and boulders, protruding from the streambed, atch and hold it against the current. Gradually, maller sticks begin to collect against the larger iece, providing a framework on which leaves can ccumulate. Ultimately, the structure becomes lmost watertight, creating an upstream pool.

nly recently has the role of organic-debris dams n stream ecosystems been recognized (Zimmerman t al. 1967, Heede 1972, Swanson et al. 1976, wanson and Lienkaemper 1978, Bilby 1979, Keller nd Swanson 1979, Keller and Tally 1979). Debris ams are important in the development and maintennce of stream-channel morphology, and they also elp to regulate the transport of particulate--and o a lesser extent, dissolved--materials through a tream system.

In the White Mountain region of New England, irst-order (Strahler 1957) streams generally are .6 to 2.4 m wide and contain from 20 to 40 rganic-debris dams per 100 m of stream channel. The frequency decreases to between 10 and 15 dams in second-order (2.5- to 2.8-m-wide) streams and rom 1 to 6 in third-order (3.7- to 6.6-m-wide) treams (Bilby 1979). Organic debris dams are are in streams larger than third-order. Debris ams contain 75, 58, and 20 percent of the total tanding stock of organic matter in first-, econd-, and third-order streams, respectively. Therefore, these structures are currently mportant in regulating sediment routing only in eadwater streams. The questions we wish to ddress in this paper are: What factors are esponsible for creating the relationship between tream size and frequency of organic-debris dams in streams in mountainous areas of New England? How variable is this pattern over time?

## DEVELOPMENT OF ORGANIC-DEBRIS DAMS

The effect of precipitation and vegetative cover on erosion are well known (e.g., Ursic and Dendy 1965; Ralston and Hatchell 1971; Bormann et al. 1974; Patric 1976, 1977), but the role of organic-debris dams in regulating erosion and transport of particulate material over a long period (for example, as the terrestrial ecosystem recovers after major disturbance) is not known. In the absence of many data, we suggest that organic-debris dams may be just as important, if not more so at certain developmental periods, in controlling sediment transport from a mountainous landscape than are other environmental factors such as amount of precipitation and vegetative cover. We believe this because, in the absence of appreciable amounts of overland runoff, most of the eroded material originates from the stream channel. The roles and relative dominance of amount of precipitation, vegetative cover, and organic debris dams may be separated in time, however. For example, after some major disturbance which results in the removal of most organic matter (as would occur during catastrophic events such as glaciation or a very hot fire), amount and intensity of precipitation would be the most important factors until vegetation becomes well established. With the development of vegetation and the formation of root systems, a canopy cover, and a litter layer over the surface of the ground, erosion and transport of particulate matter would be reduced. The amount of liquid water available for runoff obviously is a critical factor affecting erosion and transport of particulate matter. The amount of water is reduced by evapotranspiration (mostly transpiration in northern hardwood forests), and the amount available for overland runoff is regulated by infiltration rate and storage capacity of the soil. Studies at the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire (e.g., Bormann et al. 1974) and elsewhere, however, have shown that even in forested areas where biotic factors may function at a maximum, transport of particulate matter from drainage basins is exponentially and directly related to streamflow. Initially, then, after a major disturbance, biotic factors would tend to diminish erosion by absorbing the erosive power of raindrops and by reducing the amount of liquid water available for runoff, and this regulation could occur BEFORE trees became very large. For example, Marks (1974) has shown that the leaf area of early successional species in the White Mountains may be nearly equivalent to that of later, shade-tolerant dominants in only 4-6 years after clearcutting.

The size of woody debris produced by these early successional forests, however, is quite small. The average diameter of the major log found in organic debris dams in the White Mountains increases as stream width increases (fig. 1). As a result, debris dams would form in only the smallest channels during early developmental phases of the terrestrial ecosystems, because the trees would be too small to block larger channels. Although a young tree may be tall (long) enough to span a stream channel, its diameter (i.e., mass) appears to be the critical factor in determining whether it can maintain stability of the debris dam during extreme discharge events. As the trees become larger, dams would form in larger channels farther downstream and further reduce the transport of particulate matter (fig. 2).

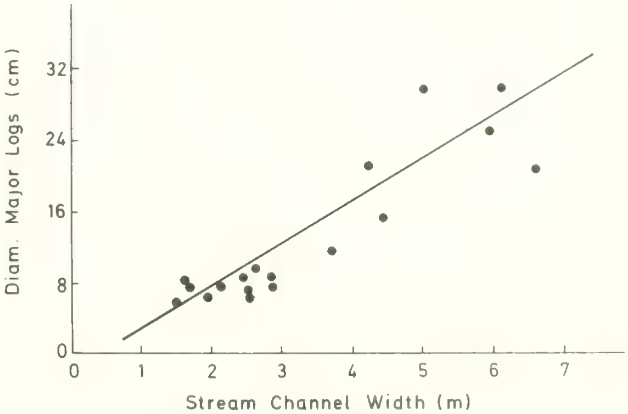

Figure 1.--Relation of stream-channel width to the average diameter of the largest member of an organic debris dam sampled in the White Mountains of New Hampshire ($Y = 4.50X - 1.73$; $r^2 = 0.79$).

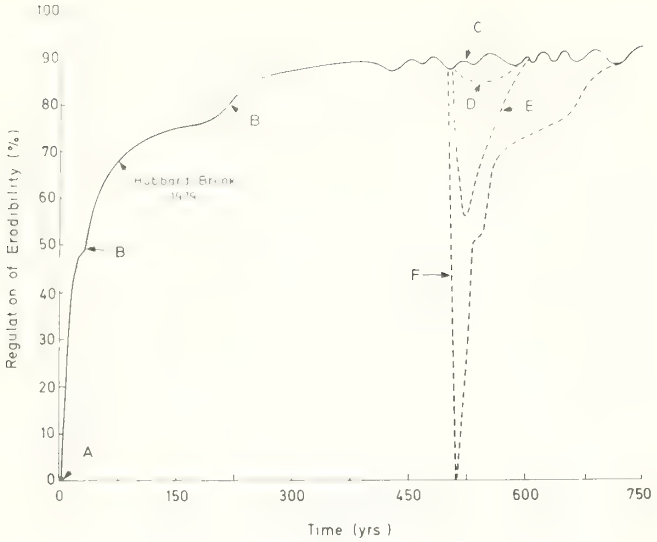

Figure 2.--Change in the regulation of erodibility with time:

A. Development of a young forest (small trees, low density).
B. Successional events when organic-debris dam formation is common.
C. Vegetative cover and organic-debris dam development complete, regulation of erodibility in steady state (characteristic of climate, vegetation type, and topography).
D. Short-term disturbance to vegetative cover only.
E. Sustained disturbance to vegetative cover and loss of organic-debris dams.
F. Sustained disturbance to vegetative cover with loss of surface humic layers (litter) and organic-debris dams.

At Hubbard Brook, a 15.6-ha drainage basin (Watershed 2 (W2)) was experimentally deforested in the autumn of 1965 and treated with herbicide for 3 years afterward to prevent any vegetative regrowth (Likens et al. 1970). Vegetation was allowed to regrow after 1969. Although no physical damage was done to the streambed during this operation, the greatly diminished input of terrestrial organic matter to the stream and increased discharge of water resulting from greatly reduced transpirational losses (cf. Hornbeck and Gee 1974) must have led to the destruction of many of the organic-debris dams on this stream. Increases in sediment yields from this drainage basin were relatively small during 1965-66 and 1966-67, but in 1967-68, they were more than 6-fold greater than on nearby uncut drainage basins and rose to 11-fold greater in 1968-69 (Bormann et al. 1974). Because essentially no overland flow occurred in the deforested drainage basin, much of this increased sediment yield must have originated from erosion of the stream channel and adjacent forest floor.

In the summer of 1976, the frequency of debris dams on W2 was still about 50 percent less than would be expected for a stream of this size in the White Mountains. The larger pieces of woody debris forming the framework of the dams, which were present in 1976, appeared old and weathered. These logs also were commonly larger than any of the trees now growing on the drainage basin. These dams thus originated before the clearcut. New dams now have formed on the first-order tributaries, but not in the second-order stream, because the woody debris produced by the forest is not yet of sufficient size to block the second-order streams. Erosion and transport of particulate matter, however, have now been reduced almost to uncut levels, primarily because of reestablishment of biotic regulation in the terrestrial ecosystem by the regrowing vegetation. In contrast, the experimental removal of all organic-debris dams from a 175-m stretch of a second-order stream in forested Watershed 5 (W5) of the Hubbard Brook Experimental Forest led to a 6-fold increase in the export of organic and inorganic particulate matter and a 6-percent increase in the export of total dissolved substances during a 12-month period (Bilby 1979). Thus, the increase in sediment yield observed from W5 after removal of dams was about the same as that observed on W2 during 1967-68. These results support our hypothesis that organic-debris dams are a major factor in regulating the loss of particulate matter from forested ecosystems.

These patterns suggest that the amount of organic matter stored in the streambed may change appreciably after disturbance and during the subsequent developmental sequence of the terrestrial ecosystem and that this organic matter in the stream channel plays a critical role in regulating erosion and transport of materials from the landscape.

## A STEADY-STATE CONDITION?

We currently believe that, within the Hubbard Brook Experimental Forest, the amount of organic debris in the first- and second-order stream channels is near steady state on an annual basis (Fisher and Likens 1973, Bormann et al. 1974), but how did this come about? According to our hypothesis, streams have not always been in steady state relative to the accumulation of organic matter. That is, after glaciation, organic matter accumulated in stream channels as debris dams formed or possibly developed downstream when larger and larger structural components became available; after major disturbance (e.g., deforestation), initial losses of organic matter and debris dams are followed by accumulation as the terrestrial ecosystem recovers. Currently, no trees are large enough to span and maintain position during flood conditions in the main Hubbard Brook channel (a fifth-order stream).

Bormann and Likens (1979) have proposed a model for biomass accumulation in northern hardwood forested ecosystems after exogenous disturbance such as clearcutting (fig. 3). According to this model, living biomass accumulates for about 170 years, during which time the trees increase greatly in size. After about 170 years or so, these trees begin to die and fall over in increasing numbers. Eventually a condition called the shifting-mosaic steady state is reached, where patches of young, intermediate, and some old trees are interspersed on the landscape. These small, even-aged patches are caused by the endogenous disturbance as trees fall over.

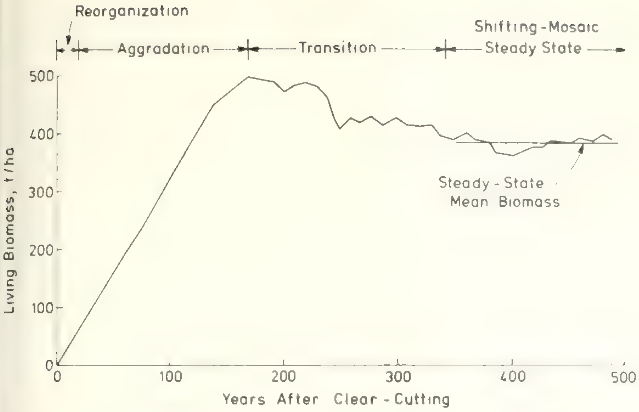

Figure 3.--Changes in living biomass during ecosystem development after clearcutting of northern hardwood forests. Phases of ecosystem development are: Reorganization (I), Aggradation (II), Transition (III), and Steady State (IV) (modified from Bormann and Likens 1979).

An important question relative to the role of organic-debris dams in streams is whether they respond to these changes by "moving" up and down the stream depending upon the size, shape, and species of tree available to produce the principal member in the organic-debris dams. Presently at Hubbard Brook, organic-debris dams are rare in streams with a mean channel width greater than 7 m. The last major cutting of the Hubbard Brook forest was in 1900-17 (Bormann et al. 1970), however, and most of the trees have not yet reached full size. The diameter and height expected of mature individuals of the dominant tree species at Hubbard Brook are listed in table 1. Assuming the relationship between diameter of the major member of an organic-debris dam and stream-channel width (fig. 1) holds true for larger logs, and that when one of these boles falls into a stream the diameter of the section crossing the channel is about equal to the diameter of the bole at half the height of the tree, we can estimate the width of channel that could be blocked by mature trees at Hubbard Brook (table 1).

Thus, before extensive logging took place in the Hubbard Brook Valley, a significant number of organic-debris dams may have occurred in stream channels up to almost 10 m in width (fifth-order). At the present time, stream channels of this size are completely devoid of debris dams. Therefore, even 60 years after a logging operation, which presumably resulted in the loss of many of the organic-debris dams from the stream systems, the drainage basin-ecosystem still has not regained its full potential to regulate sediment routing.

Obviously critical to our hypothesis are conditions that result in the falling over or blowing down of large trees. Bormann and Likens (1979) suggested that this is an important type of endogenous disturbance in the natural development of northern hardwood ecosystems. Is the falldown or blowdown of trees a random event on an areal basis? Obviously, if a large tree falls across the stream channel, the potential to form an organic-debris dam is much greater than if the tree falls in some other direction. We do not yet know whether more trees fall along a stream channel and toward a stream channel than elsewhere in a forest. If the stream channel is more than a few meters wide, this treeless zone could act somewhat like the edge of a forest where trees are more vulnerable to blowdown. Increased treefall along a stream channel might also result from increased erosion of the banks. If so, then this would be a type of positive feedback with the terrestrial system in the development and maintenance of organic-debris dams. In fact, the very presence of organic-debris dams may put more erosive pressure on the streambank (Zimmerman et al. 1967) and, thereby, enhance treefall at that spot.

Table 1--Diameter at breast height (d.b.h.) and maximum height commonly reached by the most important tree species at Hubbard Brook, and the steam channel width that could be blocked by a piece of debris equal to the diameter at half the tree height

| Species | D.b.h. commonly[1] reached by mature trees | Height commonly[1] reached by mature trees | Diameter at half[2] the height | Stream channel width that can be blocked |
|---|---|---|---|---|
| | Centimeters | Meters | Centimeters | Meters |
| *Fagus grandifolia* Ehrh. | 90 | 24 | 48 | 9.5 |
| *Fraxinus americana* L. | 90 | 24 | 48 | 9.5 |
| *Tsuga canadensis* (L.) Carr. | 90 | 21 | 48 | 9.5 |
| *Pinus strobus* L. | 90 | 27 | 47 | 9.3 |
| *Betula allegheniensis* Britton | 75 | 21 | 40 | 8.1 |
| *Acer saccharum* Marsh. | 60 | 24 | 32 | 6.7 |
| *Picea rubens* Sarg. | 60 | 21 | 32 | 6.7 |
| *P. glauca* (Moench) Voss | 50 | 20 | 27 | 5.8 |
| *Abies balsamea* (L.) Mill. | 45 | 18 | 24 | 5.2 |

[1] Data from Harlow and Harrar (1950).

[2] Calculated from d.b.h. and height, assuming a conical bole.

## ROLE OF BOULDERS

Another factor rarely considered is the role of boulders in the formation of organic-debris dams. We have found that boulders are critical to the formation of organic-debris dams in stream channels in the Hubbard Brook Valley. We measured the volume of rocks protruding 10 cm or more above the streambed at randomly chosen cross sections of the stream channel and at cross sections on the downstream side of organic-debris dams. The average volume of rocks was significantly greater (students t-test at 0.05 level) behind dams than at randomly located cross sections. In streams containing large boulders, smaller logs may be able to form organic-debris dams than in streams without large boulders, everything else being equal. Very large boulders essentially divide a stream into smaller channels. We suggest that the role of boulders, so common in New England streams, should be examined before the development and role of organic-debris dams in streams can be fully evaluated.

## HISTORICAL EVIDENCE

The sediment profile in Mirror Lake provides a long-term record of erosion and transport of particulate matter in the Hubbard Brook Valley (Likens and Davis 1975). This record suggests that about 4,800 years ago major mortality occurred in the extant hemlock (Tsuga canadensis (L.) Carr.) forests surrounding Mirror Lake. Normally, after such a major disturbance to the vegetation in a drainage area, erosion and transport of particulate matter from the landscape would be expected to increase. We suggest, however, that the hemlock decline may have been a factor in ultimately reducing transport of particulate matter by providing a source of large, dead tree trunks to form the structure for organic-debris dams. As large trees, they could have blocked much larger streams in the Hubbard Brook Valley than are presently dammed (table 1), and at the same time successional vegetation could have provided appreciable biotic regulation of erosion on the landscape. In fact, Likens and Davis (1975) found that the input of material to Mirror Lake did decrease after the hemlock decline, but they attributed the decrease to focusing of the sediments on the lake bottom. At present, we cannot resolve this problem. The blight of American chestnut (Castanea dentata (Marsh.) Borkh.) in New England and the current widespread death of American beech (Fagus grandifolia Ehrh.) also may represent periods when formation of organic-debris dams are enhanced.

The sediment record in more recent times (last 200 years) suggests a more uniform or increased transport of particulate matter to Mirror Lake (Likens and Davis 1975, Moeller and Likens 1978, Von Damm et al. 1979). This might be the result of the ultimate decay of old logs that were formed in the Hubbard Brook area before extensive cutting in 1900-17 (Bormann et al. 1970). Only now are the living trees becoming large enough to again form "stable" organic-debris dams on the larger stream channels in the Hubbard Brook Valley.

How long do organic-debris dams last in New England streams once formed? A cesium-137 profile to a depth of 55 cm in an accumulation of sediment behind a large organic-debris dam on Bear Brook in the Hubbard Brook Experimental Forest indicated no difference in age from top to bottom, implying that the sediment has been either homogenized frequently by biological or physical activity, or that it was formed within the last 25 years and all at once. How long might a log be expected to last under such conditions in an organic-debris dam? In streams in Oregon with coniferous vegetation, organic-debris dams may last for a hundred years or so (Swanson and Lienkaemper 1978).

## TEMPORAL PATTERNS OF ORGANIC-DEBRIS DAMS

What role does the type and form of vegetation play in forming organic-debris dams? How does the density of wood affect the formation and maintenance of organic-debris dams as terrestrial ecosystems develop with time? How does the growth form (height and diameter of bole) of trees affect the development and maintenance of organic-debris dams? How does susceptibility to blowdown (e.g., life history and type of root system) of trees change with ecosystem development and affect the formation of organic-debris dams? How does variable resistance to decay affect organic-debris dams? Normally, such factors are not considered when questions about the history of erosion or land use are raised, but we suggest that these factors are of utmost importance in evaluating long-term landscape interactions. Indeed, the vegetation of the White Mountains has changed rather dramatically since glacial retreat some 10,000 to 15,000 years ago (Likens and Davis 1975). Is there a characteristic steady-state condition for amount of organic debris stored in the stream channels of the ecosystem for each dominant type of vegetation?

We suggest that the type of tree can be very important in the formation of organic-debris dams. In some western U.S. forests dominated by large, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) trees, organic-debris dams are found on larger streams than in hardwood forests on the east coast merely because the Douglas-firs are larger in diameter and taller (Swanson et al. 1976, Bilby 1979). Thus, with ecosystem development whereby trees increase in size and species composition changes, we would expect organic-debris dam formation and longevity to change accordingly.

Hypothetical patterns for the formation of debris dams over time in three different sizes of stream channels after logging of a previously undisturbed forested ecosystem in the White Mountains of New Hampshire are shown in figure 4. In small streams (fig. 4A), the slash produced during the cutting is large enough to block the channel; hence, the frequency of relatively small dams would increase immediately after logging. The slash decomposes and dam frequency drops until pin cherry (Prunus pensylvanica L.f.) trees, which are an extremely common and short-lived (~30 years), early successional species in the White Mountains (fig. 4D)

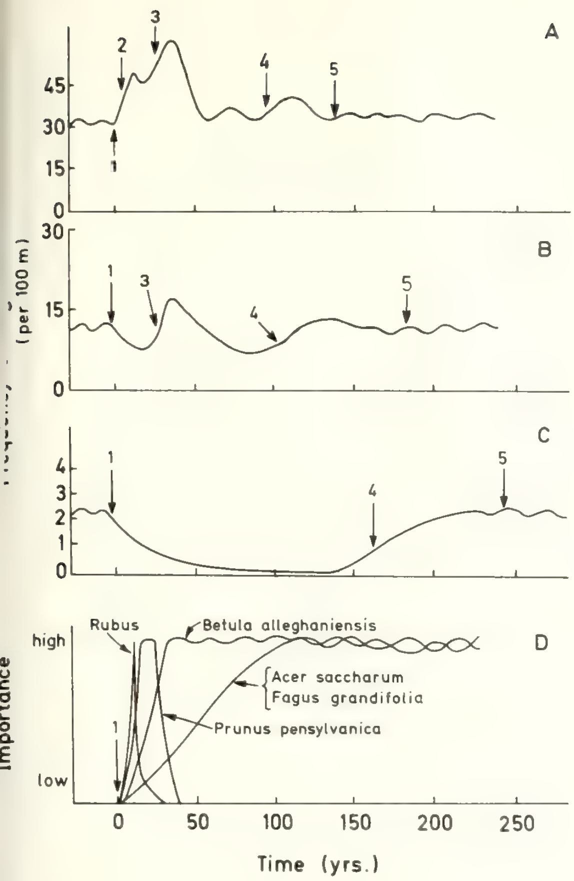

Figure 4.--Hypothetical changes in the frequency of organic-debris dams over time in first-order (A), second-order (B), and third-order (C) streams in the White Mountains of New Hampshire and in the relative importance of major plant species over a successional sequence (D) (from Marks 1974):

1. Clearcut logging of the drainage basin-ecosystem.
2. Slash enters channel and causes increase in organic-debris dam formation.
3. Falling pin cherry trees enter stream channel and form debris dams.
4. Mature, late-successional tree species begin to fall and enter stream channel, forming debris dams.
5. Return to precutting, steady-state condition.

begin to die and fall over. This input of organic matter produces a second peak in dam frequency. The dams formed from pin cherry and remaining slash then decompose as the forest grows. Eventually most of the early successional dams disappear and conditions previous to cutting are reestablished.

In slightly larger streams (fig. 4B), slash is not of sufficient size to block the channel. As a result, frequency of organic-debris dams decreases after clearcutting because of the reduction of organic matter. When pin cherry trees are dying, an increase in dam frequency occurs. The pin cherry dams decompose and dam frequency drops until the forest around the stream begins to produce woody debris large enough to block the stream.

In still larger channels (fig. 4C), neither slash nor pin cherry trees are large enough to span the stream channel. As a result, frequency of dams decreases for a long period after logging. Trees must reach large size before dam formation can be initiated in these larger streams. Over 100 years may be required to return to precutting conditions in these systems. Thus, even though the upper tributaries of Hubbard Brook are now in steady state relative to organic matter, the larger tributaries are likely to be accumulating (or will be in the next few decades if the forest is not cut again) organic matter in debris dams.

We have raised more questions than answers in this short discussion, but we think these questions are provocative and important in terms of evaluating the role of organic-debris dams as regulators of erosion and transport of materials from mountainous landscapes. Clearly organic-debris dams are a common and important feature of headwater streams in forested areas. The occurrence and changing role with time of organic-debris dams in larger tributaries are less well known, but would appear to be of potentially great importance in regulating erosion and sediment transport.

## ACKNOWLEDGMENTS

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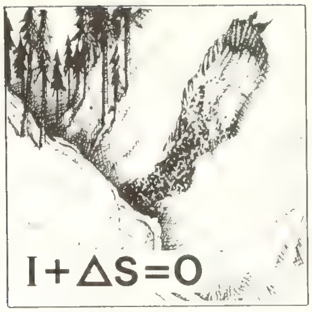

# Sediment Routing and Budgets: Implications for Judging Impacts of Forestry Practices

Frederick J. Swanson and Richard L. Fredriksen

ABSTRACT

Sediment budget and routing studies offer some improvements over traditional studies of small drainage-basin manipulations and individual erosion processes for analysis of impacts of forestry practices on soil erosion from hillslopes and sedimentation in streams. Quantification of long-term (century) and short-term (decadal) impacts awaits more detailed analysis of the dynamics of sediment storage in stream channels and at hillslope sites prone to failure by debris avalanches.

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Frederick J. Swanson, Research Geologist, and
Richard L. Fredriksen, Research Soil Scientist,
Forestry Sciences Laboratory, 3200 Jefferson Way,
Corvallis, Oregon 97331.

## INTRODUCTION

Sediment routing can be considered the conceptual or quantitative description of the movement of soil and sediment down hillslopes and through the fluvial system from one temporary storage site to another. A sediment budget quantifies the input, change in storage, modification, and output of sediment for a landscape unit. Analysis of sediment routing and budgets has been used in a variety of ways ranging from basic geomorphology research (Rapp 1960, Leopold et al. 1966, Dietrich and Dunne 1978) to analysis of land-management impacts on sedimentation (Janda 1978, Pearce and O'Loughlin 1978). Application of sediment routing and budget studies in basic research has been rare, and their use in applied geomorphology has been even more limited.

With further development, these approaches to understanding geomorphic systems will greatly aid in analyzing and mitigating effects of forest practices on soil erosion and sedimentation in streams. A sediment budget provides measures of the relative importance of both natural sediment sources and sources induced by human activities. The persistence of sediment sources is dependent on the volume of sediment stored at a site and the rate of sediment resupply, which can be described by sediment budgets. Efficient, economic solution of erosion problems begins with identifying the major sediment sources so corrective actions can be applied at the most beneficial points in the system.

Current land-management issues on a broad scale concern identification of cumulative sedimentation impacts of progressive development of forest drainage basins and use of timber-harvest scheduling to minimize these impacts. Some understanding of sediment movement through a whole drainage basin is an essential starting point in evaluating cumulative, long-term impacts of forest practices. This whole-basin perspective should also be an important part of planning future research on effects of forest management on sedimentation.

Traditional assessments of erosional impacts of forest practices have taken a more narrow approach, emphasizing studies of individual erosion processes and small drainage basins. A process, such as surface erosion or shallow, rapid, soil mass movement,[1] may be considered in isolation. The rate of a particular process may be measured in forested and disturbed areas and compared. Small drainage basins are treated as "black boxes" and their water and sediment yields are compared before and after treatment and with a control basin. Linking studies of processes and small drainage basins for better interpretation of sediment sources is a first step toward understanding sediment routing in a landscape.

In this paper, we discuss examples of results and limitations of studies of certain individual processes and of small drainage basins for quantifying impacts of forest practices on sediment routing. Reexamination of these studies leads to suggestions for improved design of future investigations of management effects on sediment routing. These suggestions are generally summarized in the basic rules for developing a sediment budget.

Dietrich et al. (this volume) outline requirements for quantifying sediment routing: identify and quantify storage sites in the landscape; identify and quantify processes that transport material between storage sites; and determine linkages among transfer processes and storage sites. These are the necessary and sufficient steps for quantifying sediment budget, assuming the system is in steady state. In studies of long-term sediment budgets for natural forest and landscape conditions, this assumption may be reasonable. In assessing effects of management activities on sediment routing, however, it is commonly necessary to account for large, relatively short-term changes in sediment storage, which preclude the steady-state assumption (Pearce and O'Loughlin 1978). Management-induced changes in sediment storage may occur in more than one type of storage area, and the changes may not all have the same sign.

Here we argue that analysis of changes in sediment storage provides useful understanding of some short-term and many long-term impacts of management practices on sediment routing. To make this argument, we first offer an overview of the sediment-routing system for small, steep, western Cascade drainage basins and then discuss analysis of management impacts on crucial, but poorly understood, parts of this system.

## SEDIMENT ROUTING REGIME IN STEEP, WESTERN OREGON FOREST LAND

The sediment-routing system of a drainage basin may be viewed as a variety of transport processes moving soil and sediment through a series of temporary storage sites. An example of linkages among storage sites by transport processes are shown in simplified conceptual form in figure 1 for steep, forested landscapes in western Oregon. This routing scheme is based on work at intensive study sites in the western Cascades of Oregon. The area is underlain by lava flow and clastic volcanic bedrock and forested with Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), western hemlock (Tsuga heterophylla (Raf.) Sarg.), and other coniferous and a few deciduous species. Most of the more than 230 cm of average annual precipitation falls as rain during long, low--intensity frontal storms between November and April.

In this area, creep, surface erosion, root throw, debris avalanches, slump, and earthflow are all potentially significant processes of particulate matter transport down slopes and into channels. Once in the channel, this material either enters temporary storage sites or moves as suspended sediment and bedload and in debris torrents.

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[1] Here we use the term "debris avalanche" to refer to all such mass movements, recognizing that sensu strictu debris flows, avalanches, and slides (Varnes 1978) are involved.

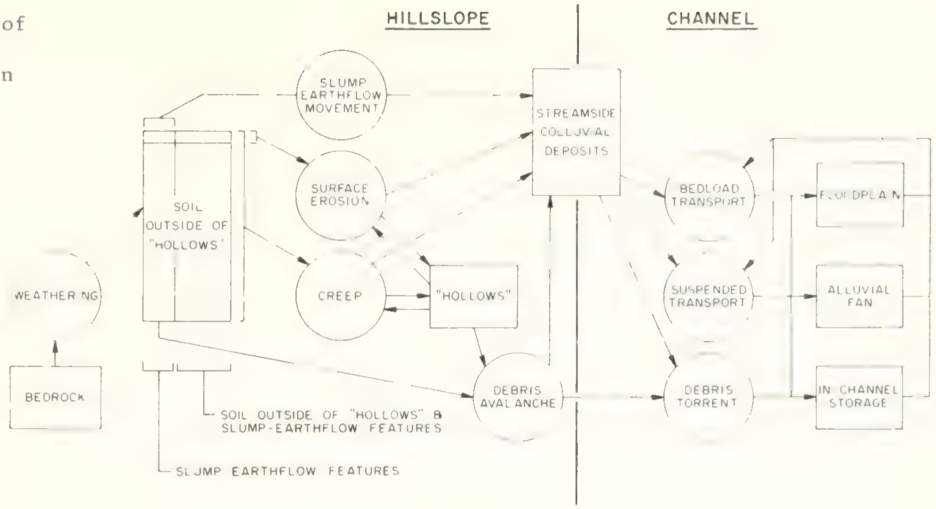

Figure 1.--Simplified flow chart of relationships among storage sites (boxes) and transport processes in steep, volcanic terrane in the western Cascades, Oregon.

Hillslope and channel processes have a variety of serial interactions in which one process may (1) directly trigger another, (2) supply sediment for transfer by another process, and (3) increase the potential for occurrence of another process. These interactions complicate sediment budgets by making it difficult to attribute sediment delivery to a point in a drainage basin to one transport process. Creep, for example, carries soil to locations adjacent to channels, but delivery to the channel occurs by surface erosion, bank erosion by debris torrents, or small mass failures of streambanks. Debris avalanches deliver sediment to channels from steep microdrainages or "hollows" (Dietrich and Dunn 1978). Debris avalanches also initiate at the oversteepened headwall and toe areas of recently active slumps and earthflows and on some planar slopes, particularly where root throw triggers events. The hollows are slowly refilled by surface erosion, root throw, and creep before being catastrophically evacuated again by debris avalanching. Sometimes, streambank cutting contributes to stream side failures, especially from toes of earthflows. Other interactions among transport processes in this landscape are discussed in Swanson et al. (1982).

Temporary storage of material occurs in a great variety of sites in drainage basins (fig. 1). The soil mantle can be considered an area of storage and divided into subunits on the basis of types of transport processes involved. Surface erosion by dry ravel, rain splash, and freeze-thaw processes, for example, affect the upper centimeter or so of the soil surface. Surface movement is faster than soil creep, which affects the entire soil column. Creep, surface processes, and rotational translational failure are superimposed in slump-earthflow terrain (fig. 1).

Storage sites for alluvial material vary in relative importance along a river system. Large organic debris commonly forms dominant storage sites in first-, second-, and third-order channels in old-growth forests. Deposits in channels not related to organic debris and flood plain deposits are the principal storage sites for alluvium in larger streams. Alluvial fans are potentially important long-term storage sites located at junctions of low-order (generally first- or second-order) channels and higher order rivers. Fans accumulate where flood plains are broad enough to provide sites for storage (Swanson and James 1975).

The sediment-routing system described above and in figure 1 is simplified and ignores important aspects of system behavior. Much of the soil movement by hillslope processes, for example, involves redistribution on slopes rather than delivery to a channel. Transfer of sediment between slope and channel areas is also far more complex than described here. Furthermore, important feedback mechanisms, such as acceleration of slope-transport processes by bank cutting and streamside mass failures, are not treated explicitly.

## DIFFICULTIES IN INTERPRETING MANAGEMENT IMPACTS ON SEDIMENT ROUTING

Studies of individual erosion processes and manipulations of small drainage basins in areas with this general type of sediment-routing system have revealed many-fold increases in soil and sediment movement after logging and road construction (Fredriksen 1970, Fredriksen and Harr 1979). Several problems arise in isolating effects of different management practices and distinguishing between short-term (decadal) and possible long-term (several cutting rotations) management effects on erosion. Crucial problems are understanding and quantifying the dynamics of two important storage sites in the system: (1) sites on hillslopes from which debris avalanches orginate and (2) channel storage sites, particularly those related to large organic debris.

### Debris-Avalanche Sites

Impacts of forest practices on soil erosion by debris avalanches are commonly measured with inventories of soil movement by debris avalanches in forest, clearcut, and road right-of-way areas (Dyrness 1967, Swanson and Dyrness 1975, and others). Dietrich and Dunne (1978) and Dietrich et al. (this volume) have critically reviewed some aspects of this procedure. Analyses of debris-avalanche inventories in steep, unstable land generally have documented increased soil erosion by debris avalanches in the first few decades after clearcutting and road construction (Swanston and Swanson 1976). The increase in failure frequency in clearcut areas has been attributed mainly to reduced root strength when root systems of killed vegetation have decayed significantly, but before roots of incoming vegetation are well established (Swanston 1970, O'Loughlin 1974, and others). Road failures generally result from altered distribution of soil, rock, and water on a slope.

The effects of cutting on debris-avalanche erosion over an entire rotation (80 to 100 years in much Federal land in the Pacific Northwest) and over several rotations are unknown. H. A. Froehlich (School of Forestry, Oregon State University, Corvallis, personal communication) and others have argued informally that the 10- to 15-year period of increased debris-avalanche erosion is followed by an extended period of debris-avalanche occurrence significantly below the rate observed in the areas of older, established vegetation usually sampled to determine a reference "natural" rate. If this is true, clearcutting may alter the timing of debris-avalanche erosion, but may not necessarily increase the overall rate on the time scale of one or more timber rotations. This hypothesis cannot be tested with existing inventories of debris-avalanche occurrence because of complexities of land use and storm histories and shortness of record.

Interpreting the effects of management on debris-avalanche erosion on the time scale of a century or more depends on understanding the recharge and storage dynamics of sites that fail by debris avalanching. Disregarding roads, debris avalanches in many areas of western Oregon originate predominantly from (1) hollow sites defined and described by Dietrich and Dunne (1978) and Dietrich et al. (this volume), and (2) sites locally oversteepened by slump-earthflow movement. Hollows are recharged by surface erosion, root throw, creep, and weathering of bedrock. Debris avalanches associated with slump-earthflow features occur on headwall scarps, at breaks in slope in midslope positions, and at toes of earthflows. Continued slump-earthflow movement creates opportunities for repeated failure at these sites.

The relative importance of debris-avalanche initiation at hollow and slump-earthflow sites varies greatly from one landscape to another. Debris avalanches from hollows predominate in many steep, highly dissected areas, but earthflow activity determines the incidence of debris avalanches in terrain of lower relief sculpted by slow, deep-seated, mass movements. Both types of sites are important in the volcanic terrane of the western Cascade Range. About 30 percent of soil moved by debris avalanches in the 62 km$^2$ of forested and clearcut areas in the H. J. Andrews Experimental Forest (1950-1979) originated from slump-earthflow features.

Effects of clearcutting on the rate of debris-avalanche erosion in a landscape containing numerous sites that repeatedly fail by debris avalanching is related to the rate of recharge of those sites and effects of management practices on processes that recharge the sites. If recharge time is much shorter than the period between cuttings, the rate of debris-avalanche erosion between the period of accelerated erosion and the next clearcutting is similar to the background forest rate (fig. 2A). Under these conditions, successive cuts will have an impact on debris-avalanche erosion similar to the first cut because sites of recent failures will be recharged at the time of subsequent cuts. Where recharge typically occurs in the period of one rotation, subsequent cuts may have the same impact as earlier cuts, but the rate of debris-avalanche erosion after the period of accelerated erosion may drop significantly below the background forest rate during each rotation (fig. 2B). If recharge occurs over periods much longer than the cutting rotation, several successive cuts may progressively have reduced impact on debris-avalanche erosion because some sites that failed after earlier cuts are not ready to fail again when subsequent cuts occur (fig. 2C). This effect may also result in debris-avalanche erosion below the background forest rate between the period of accelerated erosion and the next cut.

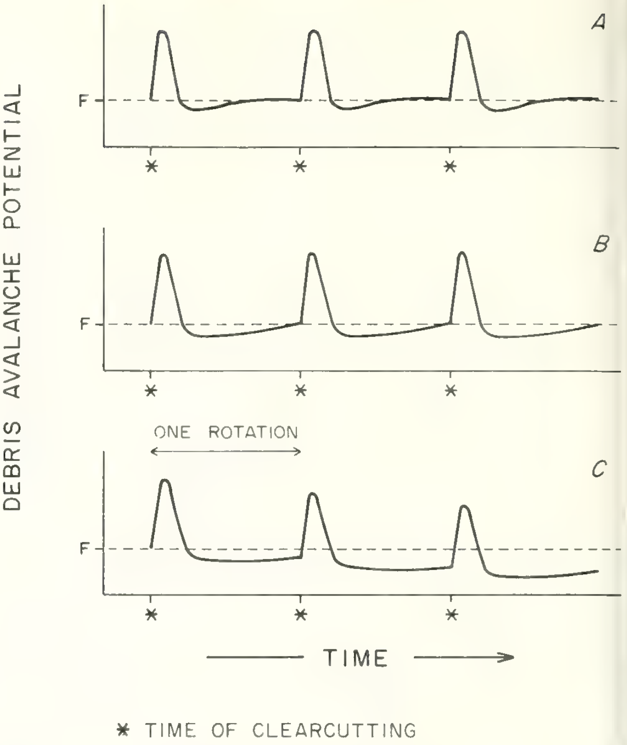

Figure 2.--Hypothetical variation in debris-avalanche potential in a landscape with many sites for debris-avalanche failure, only a few of which fail in the first 10 to 15 years after clearcutting.

A. Refilling of failed sites is fast relative to cutting frequency.
B. Refilling occurs in about one rotation.
C. Refilling takes much longer than cutting frequency.

Debris-avalanche potential rather than erosion rate is shown because actual erosion occurs in brief, infrequent periods.

Filling rates of debris-avalanche scars are poorly known. Dietrich et al. (this volume) estimate that refilling of hollows occurs on the time scale of 1,000 years, based on estimates of creep rate for forested areas. The rate may be appreciably faster if root throw, animal activity, and various surface-erosion processes are also taken into account. Furthermore, the rate of each of these processes--except root throw--may be accelerated by removal of vegetation. Wildfire, logging, and slash burning trigger periods of accelerated soil movement (summarized in Swanson 1981) which presumably causes accelerated hollow filling. How important are such periods of accelerated erosion in filling a hollow? Swanson (1981) attempted such an analysis for sediment yield in the central western Cascades of Oregon and estimated that about 25 percent of long-term sediment yield occurred in periods of accelerated erosion after wildfire. Although this estimate contains great uncertainties, it suggests that hollow filling during periods that include severe disturbances of vegetation may be significantly faster than the rate estimated for forested conditions only.

Current knowledge of the recurrence of debris avalanches from sites related to slump-earthflow features is beset with similar uncertainties. Many slump-earthflow features in this area move at rates of centimeters to meters per year (Swanston and Swanson 1976), so sites of debris-avalanche failures in slump-earthflow deposits may be recharged as quickly as in a few years to decades. Other slump-earthflows move more slowly or infrequently, so recharge of associated debris-avalanche sites is slower. Effects of clearcutting on slow, deep-seated, mass movement features have not been documented quantitatively. Gray (1970) and others hypothesize that the major effect is that reduced evapotranspiration results in increased availability of soil moisture, which may prolong seasonal periods of movement.

In summary, short-term (decadal) increases in debris-avalanche erosion after clearcutting have been documented, but effects over a whole rotation or multiple rotations (centuries) are unknown. These longer term effects are determined by rates of processes that prepare sites to fail again. All of these processes are ultimately limited by the rate of rock weathering and soil formation. Before we can assess long-term management impacts on debris-avalanche erosion, we need more information on (1) rates and mechanisms of refilling of hollows, (2) rates and mechanisms by which slump-earthflows prepare associated debris-avalanche sites for repeated failure, and (3) effects of management practices on these mechanisms and rates. Field measurements of recharge processes should be made in appropriate geomorphic contexts. It is essential to analyze debris avalanches in their overall sediment-routing context, including the storage dynamics of sites of debris-avalanche initiation.

## Small Drainage Basin Studies--Channel Storage

Manipulation of small drainage basins has been used to measure erosional consequences of forest practices. USDA Forest Service researchers have conducted this type of research on 10- to 100-ha drainages in the H. J. Andrews Experimental Forest in the western Cascade Range, Oregon. In a series of paired-basin experiments, sediment yields from control and manipulated basins are monitored and compared for periods before and after logging and road construction. Originally these studies were designed to measure impacts of forest practices on sediment yield and nutrient loss in different terrains (Fredriksen 1970, 1972; Swanson et al., 1982). As these studies have progressed, we increasingly recognized the need to understand sediment routing through each basin.

Channel-storage dynamics are a particularly important, but commonly neglected, element in the response of basins to forest cutting (Pearce and O'Loughlin 1978). The potential significance of sediment stored in channels is revealed by estimates that average annual export of coarse particulate material from small basins is less than 5 or 10 percent of sediment stored in the few channel systems analyzed (Megahan and Nowlin 1976; Megahan, this volume; Swanson and Lienkaemper 1978). Consequently, moderate changes in volume of stored sediment can account for large year-to-year changes in sediment yield, even if sediment supply from hillslopes is constant. Accelerated erosion from hillslopes may not show up as increased sediment yield if sediment is stored in channels (Pearce and O'Loughlin 1978).

Management practices can alter channel storage by (1) altering rates of sediment input and output by changing peak flows, availability of erodible sediment, and rates of hillslope erosion, (2) altering storage capacity by changing quantity and distribution of large organic debris, and (3) increasing potential for debris torrents, which can flush stored sediment and large organic debris from steep channels. Studies of experimental basins in the Andrews Forest provide examples of a broad range of changes in channel storage in response to management activities.

Unfortunately, we have insufficient data at this time to compute complete sediment budgets. Only fragmentary data exist for change in channel storage and sediment input to channels by processes other than debris avalanches. The variety of channel-storage changes, however, emphasizes the importance of quantifying channel storage in future studies of management impacts. The history of debris torrents over the past 40 years has strongly influenced patterns of sediment yield from Watersheds 1, 2, and 3, while analysis of Watershed 10 over a shorter period when torrents occurred reveals other effects of channel storage.

### Studies on Watersheds 1, 2, and 3

Measurement of suspended sediment and sediment trapped in ponding basins (here termed bedload[2]) began in 1957 at the 96-ha Watershed 1 (WS1), 60-ha WS2, and 101-ha WS3 (Fredriksen 1970). WS1 was completely clearcut without roads between 1962 and 1966, and the slash was burned in a hot fire in the fall of 1966. WS2 has been maintained as a control; it is forested with 400- to 500-year-old Douglas-fir and western hemlock, and a mix of younger trees established after a light wildfire about 135 years ago. Roads covering 6 percent of WS3 were constructed in 1959, and three areas totalling 25 percent of the drainage basin were clearcut and broadcast-burned in 1963.

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[2] Some of the material caught in sediment basins includes suspended sediment. About 25 percent of material collected in the sediment basin at WS10 after logging has been less than 2 mm in diameter.

WS1 and WS3 have responded very differently to their respective treatments (fig. 3) because of contrasts in types of treatments, timing of treatments with respect to major storms, and roles of the two channel systems as sediment sources and sinks. WS3 was freshly logged and burned when the two extreme storms of Water Year 1965 (WY1965) occurred. The storm of late December 1964 triggered a series of debris torrents, most of them initiated from roadfill failures, that sluiced out much of the drainage network of WS3 (Fredriksen 1970). These torrents carried about 20 000 t of organic and inorganic material out of the drainage basin. Over 90 percent originated from the roadfills, and most of the remainder was material stored in the channel before logging. During the following 13 years (WY1966 through WY1978), about 900 t of bedload material were exported from WS3 (annual bedload yield from WS2 has been 9.9 t/km$^2$ for WY1957-WY1976). Thus a few momentary events of WY1965 transported more than 22 times as much sediment as the entire next 13 years. The torrents greatly reduced both the volume of material in storage and the storage capacity of WS3 channel system by removing large organic debris.

The history of WS1 has been very different. The basin was only partially cut--and burning had not yet occurred--when the WY1965 storms struck, so the absence of roads and earlier stage of cutting made WS1 less sensitive to these storms than WS3. No debris torrents occurred in WS1, and most of the 800 m$^3$ of soil moved to channels by debris avalanches in WY1965 collected temporarily behind the abundant, large organic debris in the channel. Broadcast burning and some clearing of debris from the channel in 1966 initiated a period of accelerated export of bedload that totalled about 2900 t in WY1966 through WY1978. Thus bedload yield for this period from WS1 is over 3 times the yield from WS3. From measurements of channel cross sections, we estimate that about 4300 t of the material that entered the WS1 channel after logging remains in temporary storage in the channel system. The channel is now undergoing net decrease in storage. The large volume of sediment stored in the WS1 channel and unstable channel conditions suggest that bedload yield derived from these readily available sources can remain high for another decade or so.

Presence or absence of debris torrents has been an important factor in the contrasting sediment export between WS1 and WS3. Roadfills that were poorly constructed and poorly located by today's standards failed in the heads of long, straight, steep channels of WS3. These are ideal conditions for initiating debris torrents that move long distances down channels (Swanson and Lienkaemper 1978).

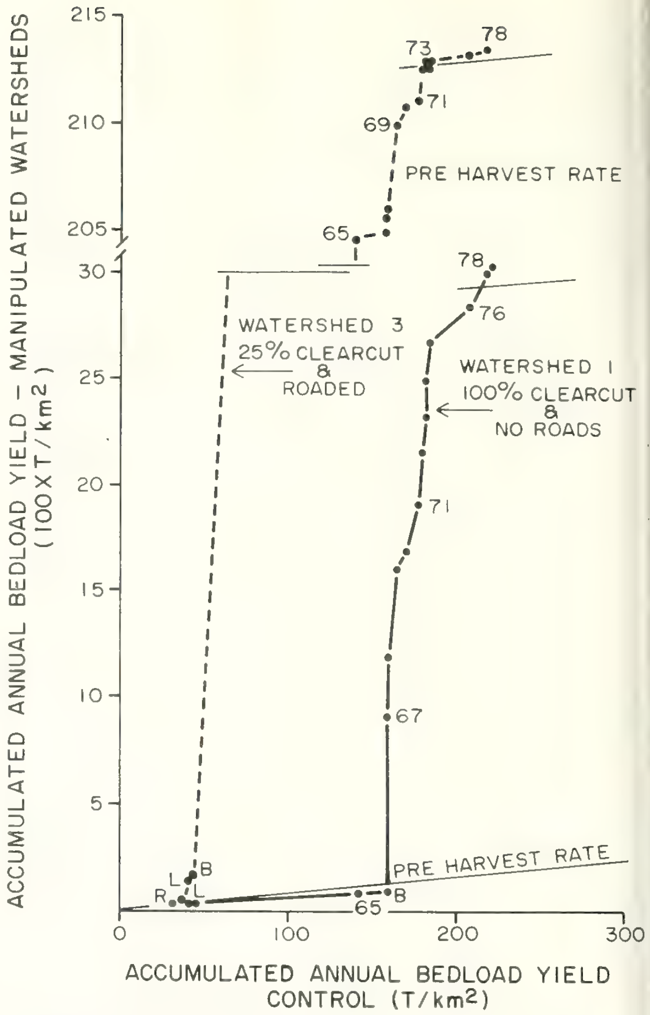

Figure 3.--Double mass plot of sediment collected in ponding basins at Watersheds 1 and 3, H. J. Andrews Experimental Forest. Preharvest rates are based on relationships between manipulated drainage basins and the control established in the predisturbance period. L = year of logging, R = road construction, B = broadcast burning.

Eight debris avalanches, each of which transported more than 75 m$^3$ of soil, have occurred in WS1 since clearcutting, but none triggered a debris torrent because they did not enter the main channel with sufficient mass and velocity and sufficiently straight trajectory to maintain momentum down the main channel.

Much of the contrast in sediment yield between WS1 and WS3 over the period of several decades after logging and road construction results from differences of channel-storage factors. WS3 was flushed and now has relatively low volume of stored material and low capacity for additional storage because of low quantities of large organic debris. Bedload export from WS3 is now limited by sediment supply from hillslopes rather than from release from channel storage. On the other hand, the timing of sediment release from channel storage is a dominant factor controlling persistent, high bedload yield from WS1, although continued sediment supply from hillslope sources is also important.

These observations point up the need in future drainage-basin studies to quantify changes in channel storage and, if possible, to distinguish material that entered the channel before and after disturbance. The mass budget equation for the channel should be: output = input + change in volume of material that entered the channel before disturbance + change in volume of material entering the channel after disturbance. Surveyed and monumented cross sections combined with stratigraphic analysis of deposits encountered on cross-section lines can be used to measure these aspects of channel-storage dynamics.

## Studies on Watershed 10

Studies at WS10 in the H. J. Andrews Experimental Forest reveal the need to account for changes in channel storage when evaluating management impacts on sediment yield in basins where torrents have not dominated the recent history of sediment export. This steep, 10-ha drainage basin was studied intensively under forested conditions from 1970 to 1975 and since clearcutting and skyline yarding in summer 1975 (Fredriksen 1972; Swanson et al., 1982). Large slash was yarded to the ridge-top landing; the basin was not broadcast burned. About half of the 50 logs that had been in the main channel of WS10 before logging were removed, and slash larger than about 5 cm diameter and 50 cm length was hand-cleaned from the channel.

Measurement of effects of logging on sediment yield is based on samples of successive storms at manipulated WS10 and 9-ha control WS9. Unfortunately, sediment-basin collections before logging were of short duration and marginal quality because of intense research activity in lower WS10, so bedload yields are compared for the postcutting period only.

Four storms during WY1976 transported 18.9 t of particulate material into the sediment pond (here termed bedload) at the outlet of WS10.[2] The first two storms produced peak flows that typically occur several times a year, yet combined they exported about 6.8 t of bedload--about 7 times the average annual bedload yield for small, old-growth forest basins (Swanson et al., 1982). The third and fourth storm events produced successively higher peak flows and exported 8.4 and 3.7 t of bedload, respectively.

WY1977 was the driest in the 86-year history of precipitation records in central western Oregon; no significant bedload transport occurred in WS10. Several major events during WY1978 exported a total of 8.8 t of bedload, although this period included two peak flows that exceeded those of WY1976. Over this 3-year period after cutting, WS10 exported 27.6 t of bedload, while WS9 yielded only 0.8 t.

These results follow two general patterns: an increase in total yield after clearcutting and a decline in total yield for a given peak-flow magnitude through the sequence of storms. Greater total export after disturbance could be attributed to increased transport capability of the system (such as increased peak flow), to increased availability of material to be transported, or both. After clearcutting of WS10, the magnitude of peak flows from snowmelt actually decreased relative to control WS9, and no detectable change occurred in peak flows for events with rainfall only (Harr and McCorison 1979). Therefore, changes in sediment export from WS10 primarily reflect changes in sediment availability and storage rather than altered basin hydrology.

Based on measurements of hillslope erosion and qualitative observations of the amount and type of material stored in the channel, export from WS10 appears to come from three sources: (1) soil and organic matter--mainly green twigs and needles--moved into the channel during felling and yarding operations, but not removed during channel cleaning, (2) material that entered the channel by natural processes before logging and had been in temporary storage behind logs in the channel, but was released from storage when logs were removed, and (3) material transported to the channel by hillslope erosion after logging. Each of these sources makes sediment available at different times. Source 1 was most significant in the first few major storms after cutting. By the fourth storm of WY1976 much of this readily transported material rich in organic matter had been flushed downstream to the basin or deposited in more stable debris accumulations within the channel. Source 2 gained importance in the first few years after logging and after material in Source 1 had been moved. Postlogging hillslope erosion (Source 3) will probably not become dominant in WS10 until several years after cutting. The timing of sediment availability from Source 3 in WS10 is a result of (1) absence of roads feeding sediment-laden water directly into the drainage system, which could supply sediment even before cutting occurs, and (2) the effect of hand-piled slash along the stream channel in retarding movement of soil to the channel. These sediment traps become less effective as they collapse from decay and snow loading. Sediment supply by debris avalanches and possibly creep is believed to increase several years after cutting in response to decay and loss of strength of roots (Swanston 1970).

This scenario could, of course, be altered in other drainage basins if, for example, accelerated surface erosion from broadcast burning or occurrence of debris avalanches soon after cutting quickly flood the channel system with material from Source 3. In WS10, though, we have measured only 1.2 t of material transported into the channel system between October 1975 and February 1976, although 19.8 t were exported. The inputs resulted from surface erosion by dry ravel, rain splash, and needle ice. Transport rates to the channel were sampled in 34 0.5-m-wide boxes located along the stream perimeter. No debris avalanches have transported soil to the channel since cutting.

The results from WS10 indicate that an understanding of channel-storage dynamics is essential to interpreting short-term (few years) data on sediment yield from disturbed drainage basins. Furthermore, changes in storage of material that entered the channel before and after logging must be distinguished. This distinction would provide better resolution of the quantity and fate of soil eroded after logging. Too often, changes in sediment yield are interpreted only in terms of altered hillslope erosion.

### Channel Storage--Long-Term Considerations

Forest-management practices can have long-term effects on quantities of large organic debris in channels and associated channel-storage capacity and aquatic habitat. Although poorly quantified, the strong positive correlation between amounts of large organic debris and stored sediment in small, steep, V-notch channels is obvious in field reconnaissance. Presence of large debris in steep channels also benefits aquatic ecosystems by providing cover, a source of nutrients, diversity of aquatic habitats, and depositional sites where organic matter can accumulate and be available for consumption by aquatic organisms. The sediment storage of large debris may also benefit aquatic organisms by buffering areas downstream from sites of pulses of sediment by processes such as debris avalanches. Downstream movement and subsequent accumulation in higher order channels may cause damage to structures, blocks to fish passage, and other problems.

When a channel such as in WS3 is flushed by a debris torrent that removes large debris, the period of recovery of debris loading and associated capacity for sediment storage may span several decades to a century or more if a source of large woody debris is available. Clearcutting without leaving trees along the channel removes the future source of large debris. Unless we specifically manage streamside stands to produce large debris for streams, little significant woody material will enter streams in managed stands. Intensive silviculture and harvesting practices produce no large woody residues.

Concentrations of large debris have persisted in streams affected by natural wildfire disturbances in western Oregon forests (Swanson and Lienkaemper 1978). Large pieces carried over from the previous stand had residence time greater than the time it took the postfire stand to grow trees large enough to produce large debris. Consequently, debris loading and associated sediment storage was likely to be maintained through the period of recovery after natural forest disturbances.

Unless the ecosystem is consciously managed otherwise, the net effect of intensive forest management is likely to be a gradual, widespread decrease in large organic debris in streams. The sediment-storage capacity of high-gradient, low-order portions of channel systems would decline greatly, and travel time of coarse particulate matter through such stream reaches presumably would be reduced. Reduced diversity and area of prime aquatic habitat is also a likely result.

Further quantification of the role of large organic debris in sediment storage throughout a river network would help strengthen arguments for or against this hypothesis. Analysis of rates of input of large debris to channel sections with different histories of flushing and disturbance of adjacent stands are also essential to predicting long-term impacts of management activities on roles of channel storage in sediment-routing systems.

## CONCLUSIONS

We have traditionally measured effects of forest practices on soil erosion and sedimentation with studies of individual processes and small drainage basins. Viewing the problem of impact assessment from the perspective of overall sediment routing suggests specific ways to strengthen our understanding of impacts on soil and aquatic resources. Sediment-routing concepts encourage analysis of storage sites as well as transfer processes and analysis of each in the context of the whole system. Use of this approach to reexamine studies of management effects on debris-avalanche erosion and sediment yield from small basins reveals numerous unanswered questions, particularly in terms of impacts over periods greater than a few decades.

Debris-avalanche inventories document short-term (decadal-scale) increases in debris-avalanche erosion after clearcutting. Determining longer term (century-scale) impacts is contingent on understanding the types and rates of processes that refill storage sites subject to failure by debris avalanche. Field installations to measure these recharge processes should be placed in an appropriate geomorphic setting. For example, the role of creep and other processes in filling hollows should be based on measurements in microdrainages contributing soil to hollows, as well as on smooth or hummocky slopes where convergent soil and subsurface water movement does not occur or is more unpredictable than in hollows. Measuring effects of management practices on recharge processes is essential because rate of recharge is a long-term control on both the kind and degree of management impact on debris-avalanche erosion. Soil formation is the ultimate controlling factor.

Changes in channel storage regulate sediment yield from small drainage basins affected by management practices. Altering the location, size, or replenishment of large organic debris alters the sediment storage and yield characteristics of channel systems. Where basins have been treated as "black boxes," changes in sediment yield have been mainly attributed to variation in hillslope-erosion processes. Future studies should assess dynamics of channel-storage systems by using repeated surveys of monumented cross sections and, where possible, distinguishing between stored sediment that entered the channel before and after disturbance of the adjacent stand. Assessment of long-term effects of management practices on sediment storage in low-order forested channels is keyed to understanding (1) relations between large organic debris and sediment storage and (2) management influences on the role of adjacent stands as sources of pieces of large wood in streams.

These examples of research needs emerge from using sediment routing and budgeting concepts to analyze shortcomings of earlier approaches. Ultimately, management impacts will be quantified with detailed sediment budgets. For the present, however, routing and budgeting concepts provide new perspectives or analyzing management effects on geomorphic ystems and help to identify important problems or future research.

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# Discussion Group Summaries

## Evaluating and Mapping Sources and Temporary Storage Areas of Sediment

Leslie M. Reid

### INTRODUCTION

Legislation to regulate forest practices, water quality, and management of federal lands has increased the land managers' need for efficient methods of identifying and mapping sources of sediment in forested basins. At the same time, theoretical analysis of landscape evolution has led research geomorphologists to the consideration of many of the same sedimentation problems as those confronting land managers. This discussion session demonstrated that, although many of the fundamental questions addressed by these groups are identical, the approaches taken in answering those questions differ widely.

### APPROACHES AND GOALS

Land managers are interested in the effects of varying land use on sediment production. Often they are asked to map the distribution of and predict sediment production from natural as well as management-induced and management-enhanced sources. They may also wish to predict distribution of sediment sources and rates of sediment production for different management alternatives in specific areas. They are interested in such questions as how timber harvesting or roadbuilding affects slope stability in an area, how the amount of sediment currently in storage in flood plains will be affected by a change in land use, and what happens to sediment introduced into a stream system by a change in land use. Usually answers are desired quickly.

Research geomorphologists may try to answer these same questions from a theoretical standpoint. They are interested in the distribution of erosional processes, for example, in order both to understand the importance of various external controls on those processes and to infer the importance and specific influence of the processes on landscape form and development. The goal of a land manager's investigation is a prediction specific to a locale, but the research geomorphologist's goal is usually an understanding of a general principle. Such general principles may be useful to a land manager as tools for making predictions in a specific area, but if other methods give adequate results more quickly or more economically, there is no compelling reason to use a theoretical approach.

The difference in approach stems from a basic difference in intent. The land manager must answer site- or area-specific questions quickly, but the researcher is interested in elucidating general principles and has the luxury of working on a more relaxed time scale.

Land managers have used the landscape stratification approach--also referred to as terrain mapping or morphogenetic classification--to characterize erosion processes over wide areas quickly. Underlying this approach is the assumption that areas of similar climate, topography, bedrock, vegetation, and land use experience the same kinds of erosion processes, produce sediment at similar rates, and respond in a similar manner to a given land use. The criteria used to define stratification units are chosen not only because of their genetic importance in controlling distribution and rate of erosion processes, but also because they are visible on aerial photographs

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Leslie M. Reid, Graduate Student, Department of Geological Sciences, University of Washington, Seattle, Washington 98195.

Participants:
R. Brown, T. Chamberlin, D. Dethier, S. Duncan, D. Harden, M. Harvey, B. Hicks, R. Janda, A. MacDonald, M. A. Madej, W. Megahan, M. Nolan, L. Reid, J. Schramek, S. Trimble, and O. Williams

r, as is often the case with bedrock geology,
ave already been mapped. A representative area
n each defined unit can then be examined in detail
y using field mapping, transects, monitoring
rograms, or more detailed aerial-photograph
nterpretation, and the results of the studies may
e used to determine a characteristic sediment
ield, process distribution or rate, or, if a
isturbed area is selected, response to land use.
he values for a representative area are then used
o typify that unit or to provide the basis for
evised stratification criteria that are more
ppropriate for the area of interest. This method
as been widely used to evaluate slope stability
examples from T. Chamberlin, B. Hicks, and
. Megahan) and has also proved useful in
ssessing and predicting effects of logging on
hannel stability (example from O. Williams). In
his last example, topographic maps and aerial
hotographs were used to classify the channels
nto one of seven stability classes. Observations
f the response of representatives of each
tability class to a given logging practice were
hen used to predict the response of a specific
hannel to that practice.

he stratification approach cannot be used when
ite-specific answers are needed. This approach
an predict the kind of landslide likely to occur
nd the average failure frequency in an area, but
t cannot be used to determine the locations of
ndividual failures or the conditions under which
given site will fail. Nor can the stratification
pproach be used reliably to predict process dis-
ribution or response beyond the range of the
mpacts already existing on each stratification
nit. For example, a stratification-based approach
ay use data from a 10-year-old clearcutting to
redict that clearcutting of a certain basin will
esult in a threefold increase in yearly sediment
roduction from landslides. The approach can give
o indication, however, of how long the effect
ill last unless a series of progressively older
learcuts exists in the same stratification unit.
imilarly, the effect of a management plan for
hich no prototype exists on that stratification
nit cannot be evaluated. Finally, the method is
estricted to areas and processes for which con-
rolling variables are easily mapped. In areas
here debris-avalanche occurrence is controlled by
he distribution of deep soil wedges or of local-
zed bedrock joints, stratification by hillslope
radient, vegetation, and bedrock lithology, each
f which may have little relation to the primary
ontrols, would be of little value.

or such areas, an approach frequently adopted by
esearchers may be useful. Individual erosion
rocesses are conceptually isolated and the
ontrols on the rate and distribution of each
rocess are quantified (Dietrich et al., this
olume). Long-term impacts of current management
ctivities or the effects of a proposed management
ctivity may then be predicted by analyzing the
esponse of the processes to the changing primary
ontrols. Sediment production from gravel road
urfaces, for example, is largely controlled by
actors such as overland flow length, road grad-
ient, and road use. These relationships have been
efined in the Clearwater basin, Washington, and
an be used to estimate sediment yields from new road designs and use patterns by determining the effects of the changes on the factors controlling sediment production (L. Reid). If process controls are adequately understood, site-specific process rates may be predicted using a combination of this technique and a probabilistic treatment of the driving variables.

The process approach thus can be used not only to solve the same kinds of problems that the stratification approach deals with, but also to make predictions for specific locations and for conditions without prototypes. The process approach requires an initial investment of effort that may make it impractical for short-term reconnaissance work, but if more specific questions are anticipated or if the necessary scale of stratification is expected to become more detailed, the stratification criteria will need to be more process-oriented. In such a case, an initial commitment of time toward the development of a quantitative understanding of primary controls of process distribution and rate may be most economical in the long run.

## METHODS: DISCRETE SOURCES

The methods used to evaluate sediment sources can be applied to both the stratification and process approaches. Methods such as field mapping and aerial photograph interpretation are standard techniques for evaluating discrete sediment sources such as landslides. If these techniques are to be used quantitatively, however, care must be taken to avoid comparing areas of different resolution without making allowances for that difference. For example, debris-avalanche frequencies cannot be compared by counting landslide scars if the scars heal more quickly in one area than in another, and a count of scars in a logged area compared to one in a forested area has little meaning unless the size of the smallest scar recognizable beneath the tree canopy is known.

Analysis of sequential aerial photographs is of particular value in determining frequencies and recovery times for different processes, but in many areas, few photograph sets are available. A source of aerial photographs frequently overlooked is county tax records in courthouse files: since the early 1940's, governments of many timber-producing western counties have been taking aerial surveys at 4- to 10-year intervals to assess timber holdings (R. Janda, D. Hardin, M. Nolan).

Ground photographs, too, may facilitate the evaluation of past geomorphic and vegetative change or even allow the reconstruction of process distribution and rate in areas before disturbance. In addition, both sequences of aerial and ground photos may be used in conjunction with climatic records to assess the impact of specific storms (S. Duncan, D. Hardin). Historical photographs of the area of interest may exist locally, and during the 1930's the Soil Conservation Service compiled a series of high-quality photographs documenting erosion problems in each State. Though the emphasis of the series was on agricultural and range lands, other land use categories were included. The photograph collection is preserved in the National Archives (S. Trimble). The U.S. Geological Survey also maintains a collection of historical photographs (R. Janda).

Other remote-sensing techniques have recently been applied to geomorphic problems. Both aerial infrared and radar imagery have been used successfully to map areas of landslide hazard. Lineations observed on infrared photographs in New Zealand were found to correspond to moisture differences between coherent bedrock and more slide-prone, crushed zones, and thus correlated well with landslide distribution (M. Harvey). In Idaho, lineations made visible by radar imagery also correlated very well with landslides (W. Megahan). Computer-rectified side-scanning radar images, because of their fine resolution and low-angle illumination, are useful in discerning subtle differences in relief such as those produced by landslides, but like visible-light photography, radar imagery cannot penetrate forest cover. These techniques can be used not only to map sediment-source distribution, but also to help map the distribution of rate-controlling variables such as vegetation, hillslope gradient, and bedrock geology. Other controls, such as soil depth and ground-water level, are less amenable to analysis by remote-sensing techniques.

Wedges--areas of deep soil on hillslopes with otherwise uniform soil depth--are very important in determining the location of debris avalanches in some areas, yet because wedges may have little or no surface expression, they are very difficult to recognize in the absence of road cuts. Portable seismic units have shown promise in measuring soil depth if the soil-bedrock interface is distinct (S. Duncan), and a portable conductivity meter is being developed for this purpose by the Bureau of Land Management. A prototype already on the market has been used successfully in southern Oregon. The conductivity meter is used to measure the depth to a subsurface contrast in conductivity, and because such a contrast may be the result of any of several factors including material, density, and moisture differences, readings must be calibrated for each area by digging test pits (B. Hicks). Eventually an understanding of how wedges form may make possible the prediction of their frequency and distribution in specific areas.

Mapping of peak or time-averaged piezometric levels is fraught with similar difficulties. Because the temporal occurrence of landslides is so closely tied to the occurrence of major storms and thus to high piezometric levels, maps showing the probable duration of a given piezometric level may prove useful in determining landslide potential in an area (T. Chamberlin). But as yet, the use of piezometers is the only widely available method for measuring ground-water pore pressures, and the time and effort necessary to install piezometers has restricted their use to networks covering only small areas. In this case, a more process-oriented approach, where the controls on piezometric levels are determined in detail in a small area and then projected to the larger area of interest, may be most useful (S. Duncan). The technology necessary for remote sensing of soil thickness, ground-water depth, and other process controls may already exist; it may require only a closer working relationship with specialists in remote sensing to link the geomorphologist's needs with the capabilities of remote sensing.

## METHODS: DISPERSED SOURCES

In many areas, dispersed sources such as surface wash, rill erosion, and small-scale bank erosion may contribute as much or even more sediment to stream channels than large, discrete sources. Even in areas where the net contribution from dispersed sources is small, they may be important as persistent sources of fine material. In addition, dispersed sources may prolong the impact of a landslide by preventing its revegetation, and in the case of bank erosion, may locally create the potential for discrete failures.

Because of the more continuous nature of their sediment production and because they are not discernible by remote sensing, dispersed sources require a more process-oriented approach to analysis even for purposes of stratification. Empirical correlations of sediment yield with different types and intensities of land use have in the past dealt implicitly with such sources, but because these studies require a large data base and do not distinguish specific source types, they are generally useful only in broad stratification schemes.

Direct monitoring of individual sources provides information that can be projected to stratification units of any size based on the distribution of rate-controlling variables. Monitoring methods depend, of course, on the types of processes in question. Surface erosion by such processes as rainsplash and rilling has been monitored using erosion pins on slide scars and gully walls (Lehre, this volume); erosion pins have also proved useful for measuring back-cut retreat on roads. With frequent observations it is possible to isolate the effects of specific storms and freeze-thaw, and careful selection of study plots allows the isolation of other variables such as aspect, lithology, slope angle, and slope length. Gerlach troughs are effective in monitoring sediment loss from the same sources (R. Janda), as are repeated measurements of surface elevation and sediment character on erosion plots (R. Rice). Erosion-plot studies using measurement of erosional landforms such as rainsplash pedestals and gullies have also been used to estimate effects of timber harvest and road construction on soil movement (Hauge 1977). Surface erosion by overland flow on gravel roads is also a significant source of fine sediment and can be monitored by measuring sediment concentrations in surface or culvert drainage. Sites must be selected carefully to isolate rate-controlling variables such as road gradient, drainage area, back-cut contribution, road use, and storm intensity. Use of a portable rainfall simulator may add flexibility in site selection (L. Reid).

In some areas, surface erosion can be measured by observing the depth of soil profile truncation. Because profile truncation is a criterion used in describing soil series, the extent of surface erosion may on occasion be mapped directly from existing soils maps (S. Trimble). Similarly, buried profiles indicate net accumulation or storage.

## SEDIMENT STORAGE

Once sediment has entered the transport system, it may be stored for periods ranging from minutes to millions of years in landscape elements such as hollows, streambeds, gravel bars, and terraces. Though measurements of sediment production rates are important in determining the amount of sediment entering stream systems, an evaluation of sediment storage is necessary if the location, magnitude, and duration of the long-term impacts resulting from sediment production are to be determined. In addition, many sediment-related impacts of major concern involve a change in the location of sediment storage or in the character and amount of the material stored; such impacts include stream siltation, infiltration of fine sediment into spawning gravels, filling of pools, and channel destabilization. Finally, any accounting of sediment production that attempts to relate production rates from individual sources to a basin sediment yield must also take account of changes in volume of material in storage, because sediment may be either gained from or lost to storage during transport.

Trimble (1981) demonstrated the importance of this effect for the Coon Creek basin in Wisconsin, and further suggested that the present sediment load of many streams was determined by basin conditions over past decades or even hundreds of years. At Coon Creek, sediment originally produced by poor agricultural practices in the late 1800's was stored in the uplands for several decades. By the 1930's, it had been transported downstream as far as the main valley, resulting in massive aggradation of flood plains, even though agricultural practices had improved markedly by that time.

Similar effects are seen in the movement of sediment waves through stream systems. Coarse sediment introduced into a river at a point (as from a landslide) may travel as a slow-moving wave that may be recognizable only as an otherwise anomalous local change in channel morphology. This sediment is effectively in storage and is moving independently of any processes occurring at its source; its major impact at a downstream point will not be felt until the wave of sediment reaches that point. Such effects have been described in western Washington (Madej, this volume), northern California (Kelsey 1980), New Zealand (M. Harvey), and elsewhere. Thus, an analysis of sediment storage is necessary to answer such questions as what happens to sediment once it enters the transport system, what areas will be affected by an increase in sediment production, how long will the impact persist, and how will material already in storage respond to a change in land use.

A major problem in the evaluation of sediment storage is that the distinction between a source and a sink for sediment is not always clear. Because of the continuum between transport and storage, a meaningful assessment of either must consider residence time of material (D. Harden). Most landscape elements can act in either capacity, depending on recent climatic conditions, location in a basin, magnitude of a specific climate event, or local environmental conditions. This last point is of special interest, because it implies that a change in land use, and thus in factors such as local water balance or apparent soil cohesion from root strength, may be large enough to convert storage elements into active sources.

Location within the drainage network is also important in determining the response of a storage element to changing conditions. In the northern California Coast Range, for example, small headwater streams tend to aggrade their beds during small storms and degrade during large, peak-flow events, but sediment aggrades in larger streams during large events and is gradually eroded during the smaller ones (Janda 1978).

A further complication to the analysis of sediment storage is the discontinuous nature of sediment transport. Transport of gravel is accomplished by the alternation of long periods of stationary storage on the streambed with brief episodes of rapid transport during storms. Similarly, flume studies in Colorado suggest that coarse material introduced into a stream is transported as a series of prograding fans in channels (Harvey, this volume). A clast is stored in any given fan for a relatively long period before it is once again eroded out and transported to the toe of the fan. In each case, the sediment in "active" transport spends a large proportion of its transport time in storage.

On a larger scale, entire landscape elements may be undergoing similar cycles. Hollows, for example, are thought to gradually fill with colluvium until the fill--or wedge--reaches a critical depth. At this point, high pore-water pressure during a large storm can cause it to fail. The colluvial fill is transported downslope, and the slightly enlarged bedrock depression is left to refill (Dietrich et al., this volume).

The importance of time scale is evident in each of these examples. Wedges and low-order stream channels, which appear to be stable sediment traps during most of their cycles, are seen to be net sources of sediment when observed over several cycles. In addition, the dependence of geomorphic response on storm magnitude adds a probabilistic variable to any long-term evaluation of a landscape element.

## SUMMARY

Maps based upon quantitative, process-based studies and those based upon empirical correlations of source distribution with landform parameters both have been used to evaluate sediment production. Which of these approaches is most useful depends on the purpose of the specific study, but methods that have been developed for measuring production rates can be used in conjunction with either approach. These methods include various mapping techniques, monitoring programs, and experiments. Analysis of sediment production in a drainage basin must take into account changes in sediment storage, but this is made difficult by the sensitivity of storage elements to factors such as climatic history, magnitudes of individual storms, and local physical and biological conditions. In addition, because the distinction between storage and transport is to some extent arbitrary, and because landscape elements may undergo natural cycles alternating between net sediment input and net output, the definition of sediment-storage elements is partially dependent on the time scale of interest.

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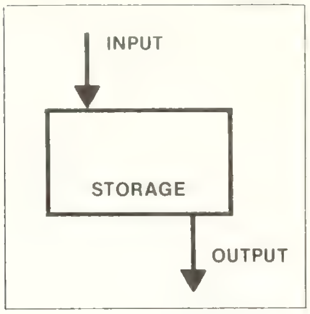

# Tracing and Dating the Movement and Storage of Sediment

Randall B. Brown and Linda B. Brubaker

## STATEMENT OF THE PROBLEM

Participants agreed that the most recent sediments, including those that are currently active, are of primary concern in tracing and dating the movements of sediment in forest drainage basins. Thus, the discussion revolved around techniques that might be applicable in dating and tracing sediments up to tens of thousands of years in age. Of interest are the rates of movement and the magnitude and frequency of sediment-transport processes. A particularly acute problem is the dating of recent alluvium in channels and terraces, and of colluvium on hillslopes and fans.

Participants further agreed that the technology is more advanced for DATING sediments than for TRACING the movement of sediment. Thus, for discussion, the two problems were separated.

### Dating of Sediment

Dendrochronology holds great promise for application in sediment budgets and routing. The central technique of dendrochronology is counting annual growth-rings in wood to date the tree; the age of the tree may then place limits on the onset or duration of some geomorphic process--such as sheet or gully erosion, deposition, or flooding at the site. Other information extracted from patterns of tree-ring width or density provide data on environmental conditions, such as drought or cold weather, which are germane to the interpretation of sedimentary records.

The range of time over which these methods are useful extends from the present as far back as several thousand years. Living or dead trees can be used and compared with accurately dated, tree-ring chronologies on file at research centers, to date sequences of ring widths. Recent developments in the measurement of density by X-rays aid in finding late-wood density patterns that are otherwise unrecognizable.

Sigafoos (1964), for example, has shown how the counting of tree rings outside of healed scars--and the bowing of trees and consequent adjustments in wood anatomy and sprouting--can indicate flood damage to trees at various elevations on a valley floor. Careful documentation and dating of these indicators allow the construction of a flood-frequency curve. Sigafoos also dated changes in rooting patterns after partial burial of tree trunks to document sedimentation on a floodplain. LaMarche (1968) measured the height of exposed roots on bristlecone pine (Pinus aristata Engelm.) trees in the White Mountains of California. The trees, which are several thousand years old, were dated by counting growth rings. Dunne et al. (1978, 1979) have used the method on much younger trees and bushes to map profiles of erosion along hillslopes in Kenya, and to indicate recent acceleration of erosion. Dietrich and Dunne (1978) used dendrochronology to define the rate of infilling of hillside hollows that had been excavated by landslides. Other studies have considered damage to live trees by fire (Heinselman 1973) and

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Randall B. Brown, Research Assistant, Department of Soil Science, Oregon State University, Corvallis, Oregon 97331; Linda B. Brubaker Associate Professor, College of Forest Resources, University of Washington, Seattle, Washington 98195.

Participants:
R. Brown, L. Brubaker, J. Christensen, S. Duncan, T. Dunne, M. Harvey, W. Jackson, H. Kelsey, T. Lisle, A. MacDonald, M. A. Madej, W. Megahan, M. Nolan, A. Pearce, G. Snyder, B. Taylor, S. Trimble, and O. Williams.

splitting by differential ground movement (Schroder 1978), which both produce rings that are not continuous around the trunk circumference. Alestalo (1971) used dendrochronology to study a variety of geomorphic processes.

One intriguing approach is suggested by the tendency for exposed tree roots to take on the character of tree stems for the duration of the exposure. Dating the sequence of change from root to stem character on cut faces can aid in the reconstruction of cut and fill sequences. Relative dating techniques might then be used to relate such cut faces and escarpments with associated geomorphic surfaces.

The width of lichen colonies is an index of the age of exposed raw materials under a constant climate (Benedict 1967). Before this approach can be applied in a given area, however, age-size relationships must be defined by the measurement of lichens on surfaces of known age. Because of the possibility of lichens invading a fresh deposit or exposure before trees, lichenometry can be a valuable tool in dating, especially in the range of tens to hundreds of years before the present.

Several isotopes can be used as markers/tracers in sediment movement studies. Lead-210, for example, is a natural isotope that falls from the atmosphere at a more or less constant rate at a given latitude, and is deposited in reservoirs and other depositional sites. Changes in $^{210}$Pb levels in depth profiles reveal periods of accelerated sedimentation rates that, in at least one instance, have been shown to correspond with historical records of human disturbance (Nevissi and Schell 1977). The technique is useful over the range of about 10 to 200 years before the present.

Cesium-137 is a nuclear-fission product with fallout levels that peaked in the early 1960's as a consequence of atmospheric testing of nuclear weapons (Ritchie et al. 1975). This isotope is attached readily to soil particles and serves as a tag on fine sediments. Its best use seems to be as a datable stratigraphic marker. Overthickening or thinning of $^{137}$Cs-rich surface layers likewise has utility in estimation of sedimentation/erosion rates.

Applications also may exist for some other geochemical techniques, such as the use of $^{12}$C/$^{13}$C ratio changes in organic materials as a function of increased burning of fossil fuels in recent times, the worldwide increases in Pb content of organisms from accelerated gasoline use over recent decades, or changes in deuterium ratios in wood.

Classical $^{14}$C dating has severe limitations over the range of tens to hundreds of years. Imprecision over this range, fluctuations in atmospheric $^{14}$C levels, contamination problems, and the complexity of interpreting $^{14}$C dates for decomposed organic materials combine to make $^{14}$C dating on very recent sediment a risky undertaking (Campbell et al. 1967, Ruhe 1975).

Historical records are a powerful tool in assessing recent geomorphic events. Stream cross sections taken in bridge design and construction work, topographic information collected in railroad construction, aerial photographs taken over the last 50 years, and other photographic records have been used with great success in assessment of modern erosion and sedimentation rates, stream-channel changes, and gullying. Historical and archeological artifacts are also of use (Leopold and Snyder 1951; Trimble 1970, 1981). Knowledge of fire and earthquake activity and major climatic events can give important clues to periods of high landscape instability in some areas.

Several other dating techniques were discussed in this session. Changes in pollen percentages in a sediment core sample, the arrival of exotic species, and other uses of time boundaries in pollen profiles can be helpful in sedimentation studies. Pedogenic processes and the degree of development of soil features can serve as indicators of age on recent geomorphic surfaces or buried surfaces. Particle-size distribution and the depth variation of grain size can help in assessing erosional/depositional history. Natural stratigraphic markers--such as volcanic ash deposits and paleosols--are useful in identifying buried, exposed, or relict geomorphic surfaces.

### Tracing of Sediment

The task of tracing sediment movement is more difficult than dating, because the conceptual methods and technology for tracing sediments are not as well developed. Nevertheless, some tracing techniques do exist and several were discussed.

Rock and mineral provenance studies, including study by scanning electron microscope of quartz-grain morphology (Glasmann and Kling 1980), are useful techniques in identifying source areas of sediment. The influence of deep-seated failures or deep gullying may be detectable with provenance studies in those instances where source landscapes have depth variations in mineralogy or degree of weathering (Youngberg et al. 1971). Thompson et al. (1980) have reviewed how the analysis of various magnetic properties of sediment can be used to identify sediment sources both after deposition of the sediment and during its transport.

Application of other sedimentological techniques developed by petrologists and engineers also have use in sediment routing. Areal/depth variation in particle-size distribution, and analysis of sedimentary structures, can be useful in assessing rates and types of transport processes.

Tracing experiments that use painted, fluorescent, or exotic rocks have limitations in natural systems. Because only a small percentage of the tagged objects are usually recovered, the fate of the majority of tagged objects is uncertain and so, thus, are the major transport pathways of the system. Also, the dynamics of the mass or pulse of sediment as a whole are not well elucidated by this technique. Participants suggested that simplified versions of such experiments, as in a rock-floored channel or a controlled, areally limited environment would be easier to interpret at the current stage of knowledge. More complex experiments could be designed later.

Use of radioactive tracers presents other problems. The controversial nature of such materials and their dilution in transport and consequent low detectability make them almost prohibitive in field studies. Tracers are more useful in controlled settings such as small flumes or small drainage-basin models. Radioactive minerals such as uraninite are traceable in small-scale bedload-transport studies.

We now have a dearth of conceptual models to describe the fate of a marked particle in a sedimentary system. Until such models are developed, designing useful tracing experiments and interpreting the results of experiments already done will be difficult (e.g., Laronne and Carson 1976, p. 82; Mosley 1978; Dietrich et al., this volume).

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# Weathering and Soil Profile Development as Tools in Sediment Routing and Budget Studies

Deborah R. Harden, Fiorenzo Ugolini, and Richard J. Janda

## INTRODUCTION

Studies of soil morphology and genesis have, for the most part, focused on sites where profile characteristics result primarily from vertical pedogenic processes and are little influenced by repeated erosion or deposition. Soil investigations at such sites may be used to place limits on the age of some relatively stable parts of the landscape (Birkeland 1974), but they are of little value in studying processes and rates of sediment movement through drainage basins. On most sloping landscapes, periodic erosion and deposition are integral factors in soil formation. Additionally, weathering and soil formation strongly influence the hydrologic and erosional characteristics of the regolith. The interactions between geomorphic and pedogenic processes have been discussed in a variety of intriguing papers (e.g., Zinke and Colwell 1965, Conacher and Dalrymple 1977, Parsons 1978); however, workshop participants believe that these concepts will have to be developed more fully before they can be used routinely in developing sediment budgets for forested drainage basins. Nonetheless, participants did cite several ways in which soils and weathering characteristics can increase understanding of some aspects of sediment routing.

Pedological and geochemical processes concurrently operating near the earth's surface contribute to the production of material that is potentially erodible. In some instances, as in the case of areas affected by podzolization, the distinction between pedological and geochemical processes is strikingly distinct (Ugolini et al. 1977). Common to these processes is weathering which changes the strength, grain size, and mineralogical composition of geological materials.

The discussion revealed that recent attempts by soil scientists to achieve professional consensus on terminology used to classify and to describe soil profiles (U.S. Department of Agriculture, Soil Survey Staff 1960, Soil Conservation Service 1975) have resulted in a complex vocabulary that is not yet widely accepted by geologists and hydrologists. Most workers discuss concepts of soil morphology and genesis in terms that strongly reflect their professional specialization and field experience in specific types of terrain. Thus, communication between researchers with different specializations or experience in contrasting terrains is sometimes difficult. The greatest difficulty is in describing profiles that reflect episodic deposition or erosion as well as weathering; such conditions are widespread on forested hillslopes. Additional complications in terminology result when stratigraphic studies indicate that deep soil horizons reflect past climatic and vegetation conditions different from existing conditions (Janda 1979). Soil horizons, e.g., B3 horizons in ultisols, considered crucial in some soil stratigraphic studies are regarded to be below the solum and in some studies of nutrient cycling and erosion processes, considered saprolite or parent material.

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Deborah R. Harden, Graduate Student, Department of Geological Sciences, University of Colorado, Boulder, Colorado 80302, presently: Geologist, Woodward Clyde Consultants, San Francisco, California 94111; Fiorenzo Ugolini, Professor of Soil Sciences, College of Forest Resources, University of Washington, Seattle, Washington 98195; Richard J. Janda, Research Geologist, Water Resources Division, U.S. Department of Interior, Geological Survey, Vancouver, Washington 98660.

Participants:
F. Bergstrom, N. Caine, C. Chesney, D. Dethier, W. Dietrich, D. Harden, B. Hicks, R. Janda, A. Lehre, R. Sidle, F. Ugolini.

Table 1--Soil properties and diagnostic horizons useful as age indicators (adopted from Yaalon 1971)

| Easily reversible, rapidly developed ($10^1$-$10^3$ years) | Less easily reversible ($10^2$-$10^4$ years) | Irreversible, slowly developed ($10^3$-$10^5$ years) |
|---|---|---|
| pH | Clay illuviation | Oxic horizon |
| Organic matter | Iron oxide accumulation | Plinthite |
| Base saturation | Physical properties | Fragipan |
| Folic horizon | (bulk density, engineering properties) | Placic horizon |
| C:N ratios | Argillic horizon | Duripan |
| Cambic horizon--------- | Cambic horizon | Calcrete |
| Gleying | Histic horizon (fire area) | Histic horizon |
| Spodic horizon | Clay mineralogy | Clay mineralogy |
| Mollic horizon | Calcic horizon | Weathering rinds |
| | Umbric horizon | Mineral etching |

NOTE: Many of the properties may be more or less reversible in different environments.
Absolute age determination methods: $^{14}C$, fission-track, thermoluminescence, $^{137}Cs$, U-series, amino acid racemization.

## STRATIGRAPHIC STUDIES

Soil stratigraphy (the use of surface and buried soils to subdivide and to correlate sediments primarily of Quaternary age (Birkeland 1974)) may be useful in constructing sediment budgets by identifying the relative stability of different landscape elements and by placing limits on frequency and rate of erosion. Participants in the discussion group compiled a table of soil properties that can serve as possible age indicators and their response times to environmental change (table 1).

Easily reversible properties, such as pH, organic material, carbonates, and others, are probably in equilibrium with existing climatic and vegetation conditions at a site, but irreversible properties, such as plinthite, oxic horizons, duripan, and others, may persist under conditions that are drastically different from those under which they developed (Yaalon 1971).

Soil stratigraphy may be used to identify relative contributions of different landscape units to the overall sediment yield from a drainage basin. Low erosion rates on hillslopes and ridges are indicated by soils displaying strongly developed profiles and by clay mineralogy and pollen reflecting climatic and vegetation conditions that have not existed for tens or even hundreds of thousands of years. In contrast, hillslopes bearing weakly developed soil profiles or active colluvium indicate more rapid erosion rates. Downslope movement of weathered colluvium or intact blocks of strongly developed soils complicate the use of soil-profile characteristics for estimating rates of erosion.

Application of erosion rates computed from measured stream-sediment discharges to only those parts of drainage basins where soils suggest active erosion provides more realistic estimates of rates of landscape development than traditional computations of drainage basin-wide denudation. In addition, areas of temporary sediment storage may be identified in the landscape, and rates of accumulation or residence time may be estimated by soil-profile characteristics.

Another potential use of soil stratigraphy in studying erosion processes is as an indicator of recurrence intervals of episodic erosion events. Different ages of landslide episodes can often be recognized by differences in soil depth and weathering intensity, or by buried soil horizons. Workshop participants believe that this type of investigation in terrain sculpted by frequent (that is, where frequency of failure at a site is on the order of $10^1$-$10^3$ years), shallow debris slides would require a refinement of existing soil stratigraphic techniques and probably the use of rapidly developing, easily reversible soil properties (table 1). In constrast, age difference between larger, more infrequent slumps and translational slides can probably be established through use of existing soil stratigraphy techniques based on slowly developing, irreversible soil properties (table 1).

Several participants pointed out that such time-dependent weathering characteristics as thickness of weathering rinds of clasts, ratios of fresh to weathered clasts, and etching of heavy minerals are diagnostic and often easier to use than soil-profile development. In some settings, differences in specific surface and subsurface rock-weathering characteristics actually give a clearer separation of Quaternary sediments than differences in soil-profile development (Burke and Birkeland 1979).

## PROCESS STUDIES

Map distributions and profile characteristics of soils in forested areas can help distinguish erosion and deposition processes operating on hillslopes. For example, some hillslopes in northwestern California that appear sculpted predominantly by creep and streamside translational slides show progressively less weathered colluvium and younger, shallower soils in a downslope direction. In contrast, some slopes that experience episodic debris avalanches show imbricate or interfingering arrangements of fresh colluvium over saprolite, or of strongly developed soils over weakly developed ones. Some hillslopes that appear sculpted by large-scale rotational slumping show intact blocks of deep, mature soils that moved downslope from stable interfluve positions. Detailed soil maps may help identify the prevalent erosional processes operating on individual hillslopes and the frequency with which those processes occur.

One model of the linkage between soil formation and hillslope erosion in regions sculpted primarily by shallow, episodic mass movement and creep assumes that rates of weathering determine availability of sediment (Dietrich and Dunne 1978; Dietrich et al., this volume). As the regolith becomes deeper and increasingly weathered, it becomes increasingly susceptible to catastrophic removal by debris slides. In terranes where the rate of production of saprolite is exceeded by its rate of removal, the rate of soil formation determines sediment production. However, in landscapes where rocks do not have to be weathered to be eroded or where mass-movement processes extend deeper than the regolith, erosion rates may be independent of rates of weathering. Workshop members also pointed out that the type and rate of revegetation may be a controlling factor in reconstituting eroded soils.

Workshop participants agreed that better understanding of weathering and soil-forming processes is necessary for developing a model of hillslope erosion. Much recent work has been done on chemical weathering in soil formation, but physical weathering processes in forested environments have been studied much less intensively. Production of fine-grained particles from exposed and buried rock surfaces disrupts primary rock structure (stratification, foliation, etc.). Some members believe this disruption is caused solely by physical disaggregation, but others think that volume changes associated with chemical weathering may aid in disrupting primary rock and saprolite structure. Some scientists use disruption of rock structure to define the boundary between the solum and the undisturbed saprolite or bedrock. In a landslide scar, accretion by sloughing into the bare surface followed by revegetation may be necessary before rock disaggregation and soil formation can proceed. The model of physical disruption of saprolite to produce the solum may be valid if shallow erosion processes are prevalent. Other landscapes may have different regimes of soil erosion and formation and of regolith formation, however. Workshop members agreed that a better understanding of these regimes would aid in applying soil studies to studies of sediment production and budgets.

Several participants pointed out that residence times in some temporary sediment-storage compartments in forested drainage basins are long enough to allow weathering to modify grain-size distributions and other physical properties of sediment and thereby influence subsequent erosion. In areas of relatively slow erosion and rapid weathering, weathering may also significantly reduce the total mass of sediment moving through the drainage basin. In these circumstances, landscape evolution can probably be understood best by working with mass budgets that include transport of dissolved solids as well as sediment (Cleaves et al. 1970; Bormann et al. 1974; Swanson et al., 1982).

## RESEARCH NEEDS

1. Refine techniques of using soil-profile development and rock-weathering characteristics to assign ages to deposits. Emphasis should be placed on the use of rapidly developing soil properties to provide finer resolution and greater applicability to younger deposits.

2. Expand criteria for distinguishing those soil properties that are in equilibrium with existing climatic and vegetative conditions from those properties that are a relic of former conditions.

3. Develop criteria for distinguishing between sediment weathered in place after transport and sediment that was weathered primarily before its most recent movement.

4. Integrate more observations of water chemistry and soil-profile development into sediment- (or mass-) routing studies in forested drainage basins.

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# Influence of Magnitude, Frequency, and Persistence of Various Types of Disturbance on Geomorphic Form and Process

Harvey M. Kelsey

The relative importance of events of various magnitude and frequency on geomorphic form and process is one of the earliest recognized basic questions of geomorphic theory, and this workshop discussion seemed to point out that the subject is not much better developed than it was when Wolman and Miller (1960) published "Magnitude and Frequency of Forces in Geomorphic Processes." We tried to focus the discussion on defining data limitations, asking the proper questions, narrowing the scope of the problem(s) to workable limits, identifying statistical sampling problems, and suggesting investigative techniques. As one participant pointed out, we are all victims of our own experience, and though our observations and backgrounds are the foundations for moving forward, they also can cause tunnel vision. We hope the range of participants to some extent removed these limitations.

The best way to summarize the discussion is to pose a set of questions and tentative statements that reflect the major concerns of the participants. Obviously, we reached no conclusions, but we did cover a number of important questions that should be confronted. We began by asking if we are interested in the effects of magnitude and frequency of events on (1) processes that sculpt landforms (shape the landscape) or (2) processes that mobilize the greatest amount of sediment out of a basin. In other words, are we to address the landform-evolution problem or the sediment-routing problem. To this end, the group posed the question, "Should we apply the problem of the effects of magnitude and frequency of events to different drainage-basin segments or sites?" For example, the following basin segments or sites can be studied:

1. Hillslope processes (e.g., debris-slide events, surface erosion),
2. "Fingertip" tributaries,
3. Main channels (higher order channels in a basin),
4. Points of output of a basin (gaging station at end of basin--the Wolman and Miller (1960) approach).

When dealing with the problem of the effects of magnitude and frequency on geomorphic process and form, must we define first whether we assume a landscape is in dynamic equilibrium (Hack 1960), whether a landscape evolves by exceeding critical thresholds (Schumm 1973, Bull 1979), or whether another model is more appropriate? Are different landscape models mutually exclusive, or are they pertinent in different time frames?

Thinking of the geomorphic event/climatic event relationship in terms of force and response is useful: climatic event = driving force; geomorphic event = response. Perhaps we need to apply magnitude-frequency analysis separately in different climatic regimes because the relationship between driving force and response varies for different climatic areas. Therefore, climatic regime as well as basin segment must be defined. Complicating the picture, significant climatic changes on the scale of $10^2$-$10^4$ years will alter the magnitude-frequency character of geomorphic response. Perhaps a cutoff point exists in terms of time period beyond which pursuing magnitude-frequency analysis is not useful because of climatic changes.

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Harvey M. Kelsey, Geologist, National Park Service, Redwood National Park, Arcata, California 95521.

Participants:
R. Beschta, R. Bilby, N. Caine, W. Dietrich, R. Fredriksen, C. Hupp, H. Kelsey, A. Lehre, S. Paustian, A. Pearce, P. Sollins, and F. Swanson.

A basic problem of magnitude-frequency studies is the need to extrapolate for long time spans from a limited period of scientific observation. This problem raises the question, can space be substituted for time? Using the example of soil hollows and related debris avalanches (Dietrich and Dunne 1978; Lehre, this volume), frequency of failure and the rate of soil infilling of the hollows can be estimated by examining the depth of soil in hollows and the occurrence of debris avalanches over a broad area for a relatively short period of time. Alternatively, the estimate can be made by analyzing the filling rate and failure probability of one hollow over a long period. If space is substituted for time in studying magnitude-frequency relations of geomorphic processes and/or form, two criteria, in most cases mutually exclusive, should be met: (1) a homogeneous sample area (similar geology, tectonic setting, and climate) and (2) a large sample area. If we cannot take a look at a long record, an alternative is the deterministic approach of applying existing theory in an attempt to extrapolate from a limited sample population.

How should we deal with channel-storage compartments in space and time as compared to slope processes in space and time, and how can changes in these compartments best be monitored? Maybe we should first ask how related geomorphic features (headwater slopes, flood plains, footslopes, interfluves) form. Then the problem might be divided among different drainage-basin segments. For example, sediment is stored in major channels at sites with different residence times: active channel, channel down to depth of scour for major events, and the part of the channel that is storing alluvium for longer periods. Each channel-storage compartment is most influenced by a discharge of a different magnitude and frequency.

When dealing with the geomorphic importance of events of various magnitudes and frequencies, distinguishing whether the system (drainage basin, hillslope, higher order channel, or other geomorphic unit) is material-limited or energy-limited or transitional between the two is important. For example, debris avalanching on steep headwater slopes in resistant, competent rock types may be limited by availability of material if the rate of weathering is slow relative to the frequency of large storms that trigger debris avalanches. A contrasting example is bedload transport in a channel reach that has recently aggraded. Here, the system is limited only by transport capability because abundant sediment is available.

Is there a characteristic frequency for each process and is there a most important frequency for each type of landscape change? Perhaps attempting to characterize the most important frequency of activity for various geomorphic processes and events in a given area over a log time scale (fig. 1) would be instructive. The recovery of various components of geomorphic systems and ecosystems to severe disturbance, such as some of those depicted in figure 1, may occur on an exponential basis, so characteristic time scales might best be described in terms of half-life. Refilling of hollows after a debris slide, for example, may occur first rapidly and then progressively slower.

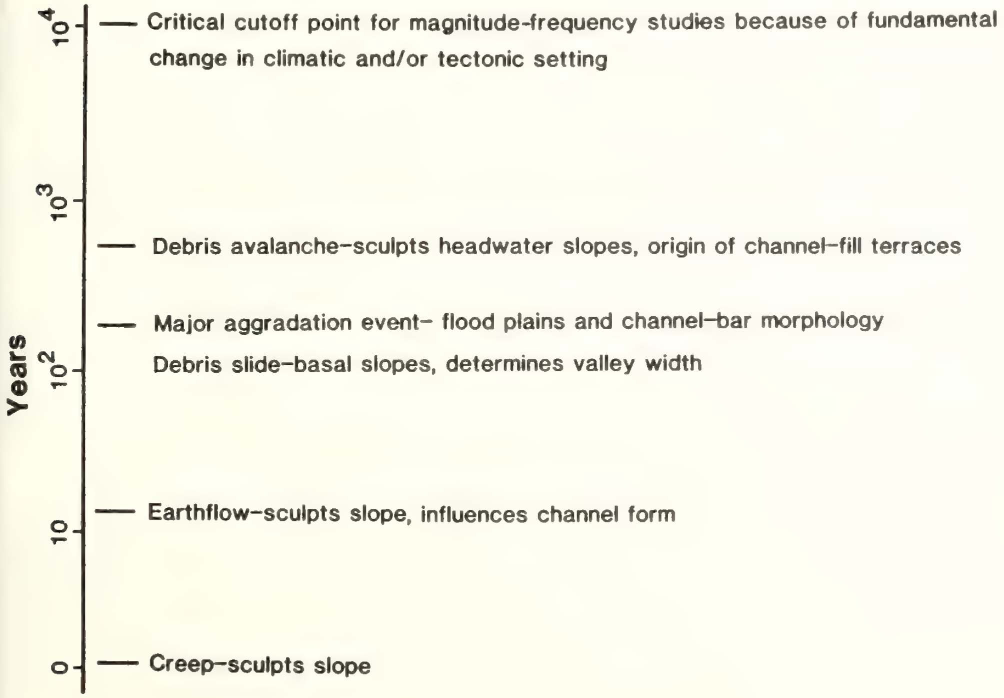

Figure 1.--Log time scale showing characteristic frequencies for different geomorphic processes.

When investigating effects of magnitude and frequency of events on process and form, we must ask whether the events are independent of each other. Magnitude-frequency analysis is most useful when independence of successive events can be assumed. Recurrence intervals cannot be used for prediction if the recurrence of one event is dependent on the last. Where records of a sufficient number of events are available, statistical techniques can aid analysis of relationships among successive geomorphic events. As Rice (this volume) and others point out, however, geomorphic change in steep lands is typically dominated by infrequent events, so a record of even 40 to 50 years is too brief for this type of analysis.

In magnitude-frequency analysis, we must distinguish between geomorphic events and climatic events. Frequency of geomorphic events and frequency of climatic events are often confused. One problem in magnitude-frequency analysis is that successive climatic events may be considered independent of one another, but successive geomorphic events may be highly related. The second of a pair of back-to-back major floods, for example, will operate on a different set of sediment-storage and streamside-vegetation conditions and therefore have different geomorphic consequences than the first flood. Independence of successive events is a basic assumption in the magnitude-frequency analysis of Wolman and Miller (1960).

Another way of addressing the same problem is to ask what is the length of memory or recovery rate of a system relative to the frequency of climatic events that trigger the geomorphic change. Expressed graphically, changes in a system may all originate from the same base level (case I, fig. 2) when recovery is fast relative to event frequency. Where events may occur so frequently that recovery from previous events is not complete (case II), the effect of any one event is determined in part by the magnitude and timing of past events. A third alternative (case III) is a combination of independent events and events that are influenced by previous disturbance.

What is human influence on magnitude and frequency of events? Land use may well be fundamentally changing the resilience and shape of the earth's surface. As a consequence, a driving force of the same magnitude may now trigger events of greater magnitude more frequently than before widespread ground disturbance. Is land use changing the character of geomorphic response to climatic events? If so, is land use likely to trigger geomorphic change in a nonlinear fashion? What is the relative importance of land use in influencing the frequency of high-magnitude as compared to low-magnitude events?

The discussion group sketched a summary figure showing some possible relationships of the magnitude and frequency of driving force and geomorphic response at different locations within a fluvial system (fig. 3). The different locations are expressed by position on a simplified longitudinal stream profile. Positions on the profile are delineated as being material-limited, energy-limited, or transitional, in terms of geomorphic process.

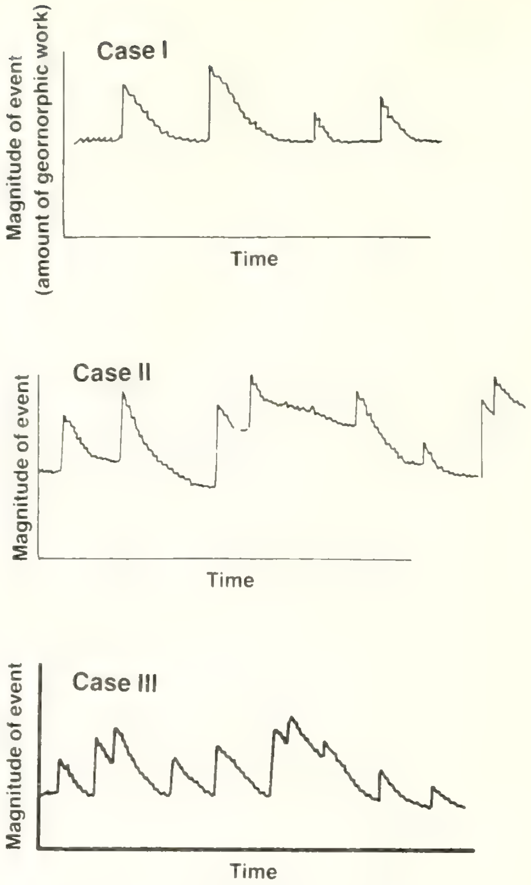

Figure 2.--Different case example of the effect of recovery rate in a geomorphic system on the magnitude of individual events in a series of geomorphic events. See text for discussion.

Participants generally concluded that magnitude-frequency analyses hold much promise for analyzing and contrasting geomorphic systems and determining minimal sampling periods for episodic events. Magnitude-frequency analysis has not been rigorously applied and examined since Wolman and Miller's original paper. Problems may arise in using this approach in systems that have strong memory (interdependence of successive events). This may be particularly true in steep, geomorphically active, forested terrain.

To better understand the magnitude-frequency characteristics of geomorphic systems, long-term data collection systems such as the Vigil Network and water resources monitoring program of the U.S. Geological Survey should be maintained. Such efforts provide both essential records of low-magnitude, frequent events, as well as some opportunity to document major, infrequent events. Further work using stratigraphic, dendrochronologic, and other methods should be employed to supplement efforts to monitor infrequent events directly, because records based on direct observation are far from adequate to answer important questions concerning magnitude-frequency characteristics of geomorphic change in geomorphically active areas.

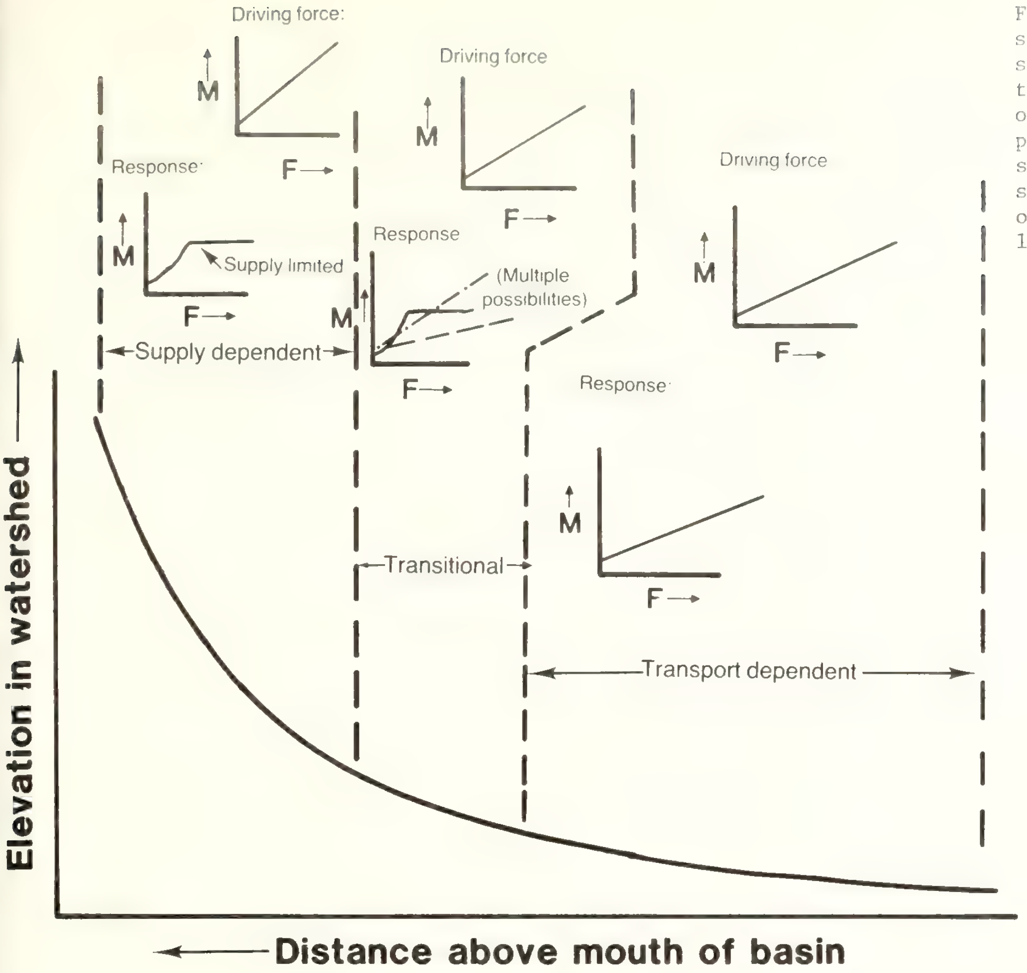

Figure 3.--Summary diagram showing possible relationships of magnitude of magnitude (m) and frequency (f) of driving force and geomorphic response at different sites within a fluvial system. Sites are depicted on a schematic version of a longitudinal stream profile.

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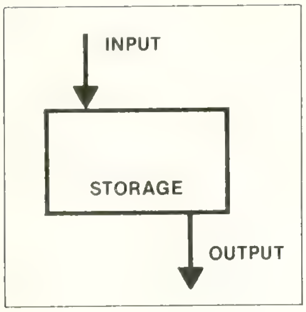

# The Use of Flow Charts in Sediment Routing Analysis

Leslie M. Reid

## THE USE OF FLOW CHARTS IN SEDIMENT ROUTING

Flow charts are a widely used means of diagramming relationships among transport processes and storage sites during analyses of sediment routing. Because they have taken so many different forms, however, it is very difficult to use published flow charts to compare geomorphic systems. Though they generally are constructed to achieve the same purpose, flow charts differ in the definition of the material being transported, type of transport processes involved, and the kinds of landscape elements considered to be sediment storage sites. In addition, the structure of flow charts may vary greatly. During this discussion, we attempted to probe the advantages and disadvantages of the different types of charts in hopes of arriving at a general form that would facilitate direct comparison of sediment budgets from different environments. Though a general form was not attained, many criteria necessary for a general flow chart, and for flow charts in general, were recognized.

Formally, a flow chart is a schematic representation of a series of operations. In the context of geomorphology, these operations are generally processes such as landslides, sheetwash, and solution transfer, which transport material from one storage site to another. Operations might also include processes such as chemical weathering and abrasion which change the character of the material, or information flow, which controls interactions between processes. Which operations are selected depends ultimately on the understanding of how the system operates, the amount of information available about the system being diagrammed, and the use to which the flow chart will be put.

Flow charts can be used to organize information, to describe a system, or to provide a framework for predictive calculations. At the least sophisticated level, a flow chart can be used to expose conceptual holes in our understanding of the relationships in a system. Such a chart need only be qualitative, though as the level of understanding increases and the recognized conceptual gaps occur at finer scales of resolution, the complexity of the flow chart and the need for quantification also increase. The same kinds of charts may be used to pinpoint critical, rate-controlling steps deserving more careful evaluation.

Flow charts are also useful for describing a specific system once data have been collected. Here, too, the level of sophistication may vary from a qualitative diagram of process interactions to a quantitative sediment budget. A corollary of this function is the use of flow charts to compare systems in different environments, and it is for this use that a need for some uniformity in structure and definitions becomes apparent. The most common means of comparison has been the single number index of sediment yield per unit area, both because it is the only parameter that has been widely reported and because it is relatively easy to measure. But important differences in processes and rates in different basins cannot be described by a single number. More useful would be a comparison based directly on sediment production and transport processes. A standardized flow-chart form would provide a means of organizing data for such a comparison.

At the most sophisticated level, a flow chart may allow prediction of the response of a basin to

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Leslie M. Reid, Graduate Student, Department of Geological Sciences, University of Washington, Seattle, Washington 98195.

Participants:
R. Fredriksen, D. Harden, W. Megahan, L. Reid, R. Rice, and F. Swanson

changes in environmental variables. The construction of such a model requires a quantitative understanding of all process rates and feedback controls operating in the system, as well as of the dependence of those rates on the driving variables.

The need for three types of flow charts can thus be recognized. Descriptive-qualitative charts organize information about relationships, and descriptive-quantitative charts attach average or instantaneous transfer rates to the qualitative framework. The third type of chart, a predictive-quantitative flow chart, includes measurements of feedback mechanisms and dependencies upon driving forces and thus allows calculation of the effects of changing conditions on the parameters of interest. Construction of such a chart, however, requires data not currently available for any natural geomorphic system.

The descriptive-qualitative flow chart has been the most widely used in geomorphology, largely because difficulties in measuring the rates of gain and loss of material to storage have prevented quantification of the charts. The traditional form of a descriptive flow chart is a series of boxes joined by arrows showing a temporal or spatial sequence. Boxes, however, can stand for many different items or concepts. Recent geomorphic flow charts have used boxes to represent (1) idealized locations as geometrically defined landscape units (e.g., units of a segmented landscape discussed by Simons et al., this volume), (2) geomorphically defined locations (swale--channel banks--channel bed of Lehre, this volume), (3) sediment deposits (soil--wedge--fan--channel bed, as described by Dietrich and Dunne 1978), (4) transport processes (creep--slump--debris slide--debris torrent shown by Swanson et al., 1982), and (5) material character (bedrock--saprolite--soil). The arrows then correspond to transport processes, weathering processes, or merely indicate sequential development.

Appropriate definitions of elements of a flow chart depend on the purpose of the flow chart. The limitations of each approach to flow-chart development must be recognized. Over long periods, for example, landforms and idealized locations may evolve from one kind to another (swales may fail, form channels, and gradually refill) and deposits may erode away or new kinds form. Storage elements, too, are difficult to evaluate, because storage and transport form a continuum that may be distinguished only by an arbitrary selection of a minimum residence time to define storage. Charts based on processes tend to be complex because most processes interact with others. Complexity is also introduced because a change in material character may be interpreted as an indirect expression of mass transfer; weathering may change bedrock to saprolite in situ, for example. In any case, care must be taken to avoid mixing different types of elements in one diagram, unless the elements are distinguished symbolically.

The more complete the flow chart, the more difficult it is to interpret, and the less useful it becomes as a graphical description of a system. Increasing complexity may be avoided by breaking the flow chart into several charts, each dealing with a separate subsystem. The subsystems may then be recombined by way of a master chart that treats each subsystem as a separate compartment. Each subsystem may represent an individual process, landform, or time segment.

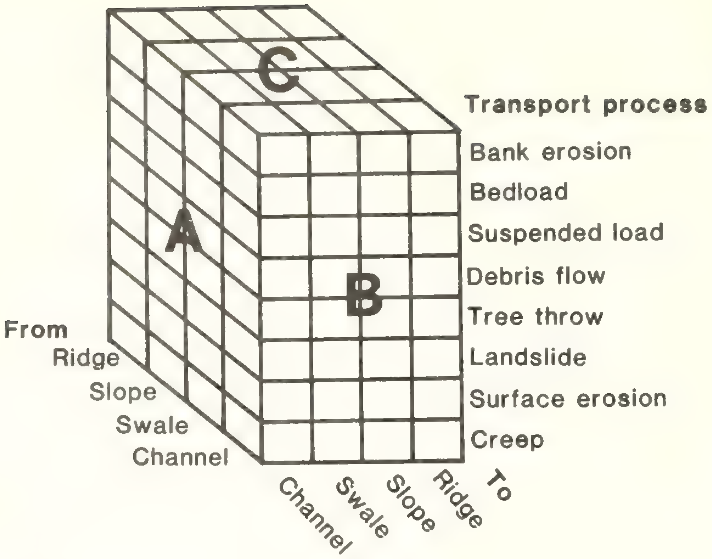
A similar approach may be used to handle the change of process type and rate as channel order increases. Debris torrents, for example, are an important transport process in steep, low-order basins. But as the channel gradient decreases with increasing basin order, torrents become less important and eventually disappear altogether. Such an effect cannot be shown on a simple chart, but if a separate flow chart is constructed for each order of channel, the effect becomes evident. These separate charts are then combined by way of a master chart that specifies the transfers between channels of different orders.

Several approaches have been used to show quantitative sediment budget data on flow charts. The relative importance of different elements or transport routes may be shown by the relative sizes of the element boxes or the thickness of interconnecting arrows, even if the actual values are not known.

If process rates and storage volumes have been measured, a quantitative, descriptive flow chart may be constructed. Rates of material transport can be shown by appending the actual transport rates to the flow chart. This method is useful in that it preserves the visual impact of the generalized chart and facilitates direct comparison of flow charts, but it becomes unwieldy as the complexity of the chart increases.

Highly complex systems can be quantitatively described using transitional matrices. With this method, locations (absolute or idealized), landforms, or storage elements are used as labels for columns and rows of a matrix (fig. 1). Sediment is considered to be transported from the location noted in a row to that noted in a column, and transport processes are differentiated by planes in the third dimension; mass transfers are filled in according to source, destination, and transport process. Sequence--an important aspect of flow charts and a critical factor in understanding a geomorphic system--is difficult to discern, but may be partially reconstructed by comparing inputs and outputs from different locations. Though visually obscure, the result makes the organization of information relatively easy and is useful in accounting; change in storage volume may be easily determined by comparing the totals in the rows and columns for each location. This operation also makes apparent the restrictions of this budget and any other descriptive-qualitative budget that is based on short-term measurements and does not deal explicitly with probabilistic variations in driving variables; the budget can reflect only what is happening at a specific time or the average result over a longer period. Otherwise, loss of material in transport to storage would imply infinite aggradation.

The third type of flow chart--the predictive-quantitative model--requires a quantitative understanding of process rates, driving variables,



**A** Destination

| | Channel | Swale | Slope | Ridge |
|---|---|---|---|---|
| Bank erosion | 3 | 1 | – | – |
| Bedload | 17 | 1 | – | – |
| Suspended load | 30 | .5 | – | – |
| Debris flow | 40 | 3 | – | – |
| Tree throw | 5 | 12 | – | – |
| Landslide | 12 | 4 | – | – |
| Surface erosion | 1 | 1 | – | – |
| Creep | – | 38 | – | – |

From swale

**B** Source

| | Ridge | Slope | Swale | Channel |
|---|---|---|---|---|
| Bank erosion | – | – | 1 | – |
| Bedload | – | – | 1 | – |
| Suspended load | – | – | .5 | – |
| Debris flow | – | 2 | 3 | – |
| Tree throw | – | 15 | 12 | – |
| Landslide | 3 | 19 | 4 | – |
| Surface erosion | – | 1 | 1 | – |
| Creep | – | 63 | 38 | – |

To swale

**C** Landslides

| From \ To | Channel | Swale | Slope | Ridge |
|---|---|---|---|---|
| Ridge | – | 3 | 1 | – |
| Slope | 28 | 19 | 23 | – |
| Swale | 12 | 4 | – | – |
| Channel | – | – | – | – |

Figure 1.--Hypothetical three-dimensional matrix for tabulation of material transfer rates between storage locations in a forested basin. Material is moved from source A to location B by transport process C. Hypothetical tabulations, in t/km$^2$ per year, are shown in 1A, 1B, and 1C. Change in storage at a location can be calculated by subtracting total output from total input at that location. In the example given, the rate of change of the volume of material stored in swales would be (total (1B) - total (1A)) = -5 t/km$^2$ per year.

and information flow; each is incorporated into the chart to form a model of the real system. When values for the driving variables are specified, the chart can be used to predict the response of any part of the system or of the system as a whole. The complexity of a realistic model, and the necessity to handle driving variables probabilistically, usually requires the model to be programmed onto a computer, leaving only the framework to be represented as a chart.

After discussing flow charts in general, we attempted to develop a general qualitative chart to describe sediment movement through steep, forested landscapes. We failed. After several hours, we had just begun to resolve the difficulties and confusion that arose in settling on a particular type of flow chart, definitions of storage sites and transport processes, and rules for showing linkages among them. The makeup of the flow chart was found to depend heavily on the specific objectives for its use, even though a general form was desired.

The consensus among discussion participants was that flow charts are extremely useful in organizing thoughts about a sediment-routing system and in comparing different landscape units. Such comparisons, however, require that flow charts be developed using a common set of rules and definitions, so that differences in flow charts for different geomorphic systems reflect real geomorphic differences. Guidance for developing a useful flow-chart form could come from other fields, such as hydrology, nutrient and energy cycle modelling for ecosystems, and network theory. Developing common definitions of landscape units and processes requires extensive discussion and a knowledge of what is geomorphically important in a wide variety of environments.

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# Summary: Sediment Budget and Routing Studies

Frederick J. Swanson, Richard J. Janda, and Thomas Dunne

ABSTRACT

Sediment budget and routing studies have been useful in dealing with a variety of basic and applied problems over a wide range of scales in time and space. Further research and application is needed to: define and quantify sediment storage; improve knowledge of mechanisms of sediment-transport processes; quantify frequency and magnitude of episodic processes; integrate biological factors into quantitative analysis of sediment budgets and routing; improve knowledge of effects of weathering on sediment routing; and mesh better the computer simulation of sediment routing with field studies of conditions in forested mountain land.

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Frederick J. Swanson, Research Geologist, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331; Richard J. Janda, Research Geologist, Water Resources Division, U.S. Department of Interior, Geological Survey, Vancouver, Washington 98661; Thomas Dunne, Professor, Department of Geological Sciences and Quaternary Research Center, University of Washington, Seattle, Washington 98195.

## INTRODUCTION

Studies of sediment budgets and routing have increased understanding of a broad spectrum of geomorphic and ecological problems (Jäckli 1957; Rapp 1960; Leopold et al. 1966; Caine 1976; Dietrich and Dunne 1978; Kelsey 1980; Swanson et al., 1982). By sediment budget, we mean the quantitative description of sediment movement through a single landscape unit; sediment routing is either the computation of sediment movement through a series of units or the more qualitative concepts of sediment movement through a drainage basin. Much early work centered on computing total denudation and assessing the relative importance of individual erosion processes. Other workers have applied sediment budget studies to practical problems associated with the effects of human activities on geomorphic processes and associated landform changes (Kelsey 1980, Reid 1981). Applications of sediment budget and routing analysis in Redwood Creek basin (California) (Kelsey et al. 1981), areas near Mount St. Helens (Washington), and elsewhere deal with a variety of management-related issues, including the persistence of high rates of sediment transport.

The basic ingredients of complete budgets are: identification of storage sites, transport processes, and linkages among them, and the quantification of storage volumes and rates of transport processes. Despite these common elements, papers on sediment budgets published here and elsewhere display marked differences in the time scales considered and the relative emphasis placed on storage and transfer processes. These differences reflect contrasts in objectives and site-specific conditions such as vegetation, land-use history, and dominant erosion process. Of particular concern at this workshop were the distinctive effects of forest vegetation on sediment storage and transport.

Although the utility of sediment budgets has been amply demonstrated, they continue to be little used. Increased application of the sediment-budget studies, even where data are seriously limited, would increase understanding of geomorphic and ecological systems--this volume was compiled to encourage such increased use. Here, we summarize some advantages of the sediment-budget approach over studies focused on individual processes or on sediment-yield data alone, six major themes that recur throughout the papers and workshop discussions, and new and continuing research needs.

## RATIONALE FOR MAKING SEDIMENT BUDGET AND ROUTING STUDIES

Enthusiasm and need for quantification of erosion and sediment transport have led to many field measurements and computer simulation models of sediment production on hillslopes and along streams. Monitoring of drainage-basin sediment yield provides an integrated, "black box" view of how sediment output from basins responds to average conditions, fluctuations in weather, and management and other disturbances. Monitoring of hillslope erosion can provide more detailed information on processes than can measuring basin sediment yield alone. This approach, however, has often been weakened by lack of attention to sampling problems and by uncertainties of how particular mechanisms fit into the sequence of processes that transport sediment out of a drainage basin. Measurement of both sediment yield and rates of processes offers little information on the role of temporary storage or the linkage between transport processes.

Some of these problems are reduced by drawing up a conceptual sediment budget or sediment-routing scheme early in the investigation of sediment movement. This requires explicit recognition of how sediment is generated, transferred, and modified during its passage through drainage basins. The initial conceptual model may be only qualitative or approximately quantitative, but it must be based on field work. Dietrich and Dunne (1978), Dietrich et al. (this volume), Lehre (this volume), and Kelsey (this volume) have all stressed the need for careful classification of transport processes and storage sites in the landscape under investigation. This preliminary analysis draws attention to the most important processes and aids the design of appropriate measurement strategies. No single approach to the definition of a sediment budget or routing scheme exists because of the variety of processes, materials, and disturbing factors even in the restricted setting of drainage basins covered by temperate forests.

Field observations of sediment transfer and storage also suggest how the accounting of sediment can be carried out. The investigator is forced to consider how sediment moves between sites and whether errors can result from adding together contributions of sediment to a channel by processes that act in series. An example occurs where soil creep merely supplies sediment to sites of landsliding which then conveys it to a channel. Dietrich and Dunne (1978) have pointed out that adding these two inputs would be double accounting and would overestimate the sediment flux to the channel.

Processes should be classified to help define the temporal and spatial requirements of a sampling scheme. Do the processes operate over extensive areas or in a limited number of restricted sites? Which processes operate persistently and which are episodic? Whether a process is viewed as persistent or episodic in part reflects the time reference of the budget. Most geomorphic measurements have been carried out over too short a time and at too few sites for adequate definition of long-term average sediment yields, their sources, controls, and response to disturbance. Field work necessary for construction of a sediment budget or routing scheme focuses attention on the need for spatial stratification of measurement sites and for lengthening the period of record by means of dendrochronological and other techniques (Brown and Brubaker, this volume).

A sediment budget or routing procedure and attendant assumptions may apply to a particular time scale only. The procedure of Dietrich and Dunne (1978), for example, is founded in the long-term view of sedimentary petrology and steady-state geomorphology. The steady-state

Table 1—Channel storage in relation to mean annual sediment discharge. Definition of channel storage varies from study to study, but generally includes readily mobilizable material. Note that (storage/annual discharge) is a measure of residence time of sediment in storage in years

| Stream (author) | Drainage area | Storage | Annual sediment discharge | Storage - annual discharge |
|---|---|---|---|---|
| | Square kilometers | | | |
| Watershed 10, OR (Swanson et al., 1982) | 0.10 | 510 t (subject to debris torrent) | 6.6 t<br>Total particulate transport including episodic debris torrents | 77 |
| Average of seven streams in Idaho batholith (Megahan, this volume) | 1.27 | 171 $m^3$<br>"behind obstructions" | 11 $m^3$<br>debris basin accumulation | 15 |
| Rock Creek, OR (Dietrich and Dunne 1978) | 16.2 | | | |
| First-order tributaries | | | | [1]19 yr |
| Third-order tributaries | | | | [1]231 yr |
| Main channel, active sediment | | | | [1]619 yr |
| Big Beef Creek, WA (Madej, this volume) | 38 | 49,200 t<br>"active, to depth of scour" | 1,000 t<br>bedload | 50 |
| Redwood Creek, CA (M. A. Madej, Redwood National Park, personal communication) | 720 | 7,200,000<br>main channel only | 1,860,000<br>total sediment load | 3.9 |
| Otamarahu River, New Zealand (Mosley 1977, cited in Pearce and O'Loughlin 1978) | | | | 35-40 |

[1] Residence time for particle entering channel of this order at midpoint of channel segment.

assumption is invalid for other time scales, however. Nonsteady-state behavior occurs where significant change in storage takes place, whether as a result of human activities or major storms (which affect geomorphic systems on the scale of years and decades), climatic change (on the $10^3$ year scale), or drainage development (on the scale of $10^3$ years and longer). Swanson and Fredriksen (this volume), for example, stress the value of not assuming steady-state conditions when examining sediment routing on the time scale of vegetation disturbance and recovery.

The sediment budget and routing approach led Dietrich and Dunne (1978) to consider the relation of weathering to transport of soil entering channels and to grain-size distribution of sediments transported down stream channels. The grain-size distribution of stream sediments is important because it influences channel form, fish-spawning habitat, sorption of nutrients and other chemicals, and rates at which large, short-lived influxes of sediment can be flushed from a system.

## MAJOR CONCLUSIONS AND RESEARCH NEEDS

### Sediment Storage

Sediment storage is an essential but poorly understood part of the geomorphic system. Geomorphologists have traditionally emphasized transport processes. Storage of sediment, however, is an equally important aspect of long-term movement of material through drainage basins. Total stored sediment, duration of storage at various sites, changes in volume of material stored, and changes in the physical properties of materials while in storage have important implications in analysis of sediment routing.

Quantitative data on sediment storage in channels is meager, but more abundant than information on storage of material on hillslopes. Available quantitative studies of sediment storage in channels in forested areas (table 1) define and measure storage in different ways. Nonetheless, these data indicate that the volume of temporarily stored alluvium is commonly more than 10 times larger than the average annual export of total particulate sediment. Mean residence times are on the order of decades and centuries. Thus, moderate changes in storage can cause major changes in sediment yield even if sediment supply from hillslopes remains constant.

Rough estimates of mean residence time of soil on hillslopes are several orders of magnitude greater. For a soil loss rate of 100 t/km$^2$ per year (on the low side of typical rates for mountain land), the mean residence time of a 1-m soil profile is 10,000 years. This is somewhat less than the residence time of soil on hillslopes computed by Dietrich and Dunne (1978) and Kelsey (this volume) for very different terrains.

Changes in sediment storage can drastically affect interpretations of erosional conditions within a drainage basin based on sediment-yield data alone (Janda 1978). The timing and magnitude of erosion of soil and its ultimate delivery as sediment to a downstream point may be very different. Kelsey (1980), Trimble (1981), and others have demonstrated that storage in channels and flood plains may delay and subdue the peak of downstream delivery of sediment introduced from hillslope sources. Conversely, increased peak flows because of altered hillslope hydrology can result in increased erosion and downstream transport of stored sediment without increased hillslope erosion (Park 1977). Management impacts on hydrology or sediment availability can therefore have cumulative effects on sediment routing downstream, an issue of growing concern in many areas of forest-land management.

Residence time of sediment in storage determines the opportunity for stabilization by rooting of vegetation on the scale of years and decades and for changes in size distribution of material by weathering over centuries and millenia. Weathering of deposits in gravel bars, flood plains, and other storage sites facilitates breakdown of sediment, thus changing the relative importance of transport as dissolved, suspended, and bedload (Bradley 1970, Dietrich and Dunne 1978). Effects of weathering are particularly important in tectonically active areas, such as the Pacific Rim--much of which is underlain by mechanically weak rocks. On the time scale of significant weathering, geomorphologists can learn much through application of the techniques developed by Quaternary stratigraphers and sedimentologists (Birkeland 1974, Tonkin et al. 1981).

### Erosion Processes--Mechanisms and Linkages

The mechanics of erosion processes and their controls are not well understood. These problems limit efforts to model movement of sediment through drainage basins. Several examples of these limitations sparked vigorous discussion at the workshop. One example is the widespread application of infinite slope assumptions to stability analysis of shallow debris slides, despite knowledge that many sites prone to debris sliding may not be well represented in hydrologic and other respects by infinite slope assumptions (Pierson 1980). This is true for "hollow" (Dietrich and Dunne 1978) and "swale" (Lehre, this volume) types of failure sites, which appear to be essentially the same and are hereafter referred to as hollow/swale sites.

Mechanics of surface-erosion processes in steep forest land in areas with low to moderate intensities of rainfall are also poorly understood, as evidenced by continued interest in applying to steeplands the Universal Soil Loss Equation (USLE) developed empirically by Wischmeier and Smith (1955) in lowland environments. The USLE was developed to estimate surface erosion by rainsplash and sheetwash on gradients of less than 20 percent. Overland flow is rare in forested landscapes. The surface-erosion processes that do operate, such as dry ravel and splash, may have very different relationships between transfer rate and slope length, rainfall characteristics, soil characteristics, and gradient than those described by the USLE.

Analysis of individual erosion processes in their overall geomorphic context is also critical. The rate or frequency of one process may be closely linked to the rates of other processes. Long-term erosion by debris slides, for example, may be limited by recharge of slide-prone hollow/swale sites by soil creep, root throw, and other processes. Thus measuring soil creep into hollow/swale sites would help in estimating rates of filling of slide-prone portions of the landscape. These data could then be used to judge effects of management practices on refilling rates as well as on initiation of debris slides. Similarly, progressive downslope movement of streamside earthflows may temporarily buttress the toe of the slope, impeding further movement. Subsequent stream erosion of the earthflow toe can remove support and accelerate movement, hence interpretations of earthflow movement rates should consider recent stream history.

Sediment transported as suspended load or bedload has been the subject of extensive, sophisticated analyses by hydraulic and civil engineers. Application of their equations in sediment-routing studies in steep forest lands is difficult, however, because sediment transport there is commonly limited by the rate of sediment supply from hillslopes, fans, and the streambed below an armor layer. These equations are not well suited for dealing with the coarse, poorly sorted sediment and large woody debris that forms the complex roughness elements typical of forested mountain streams. Channel form and pattern in these environments may be controlled by vegetation, bedrock, and hillslope mass movements rather than channel hydraulics and sediment properties that predominate in lowland streams.

### Problems Posed by Episodic Processes

Many sediment-transport processes, such as creep and bedload transport in sand channels, are persistently active, although at widely varying rates. Debris slides and other processes are episodically active for only short periods. The distinction between persistent and episodic processes are muted in dealing with periods much longer than the time between episodes of activity. Geomorphologists have had a long-standing interest in the importance of episodic processes in long-term transfer of material and landscape sculpture (e.g., Wolman and Miller 1960). Episodic processes are generally considered to be the dominant mode of sediment transport in steep forest land, but no concensus exists on how to deal with them quantitatively in studies of sediment budgets and routing. Estimating sediment transport by episodic processes is an essential but difficult part of computing a sediment budget. For example, alternative approaches to estimating debris-slide erosion have been proposed. Dietrich and Dunne (1978) and Dietrich et al. (this volume) attempt to quantify frequency of failure at a particular site; others (Swanson et al., in press; Lehre, this volume) apply a geographically broader inventory method of computing erosion per unit area and time.

An important difficulty in dealing with episodic events is evaluating the interaction of successive major disturbances within a drainage basin (Bevan 1981; Kelsey, discussion group report, this volume). The approach to magnitude-frequency analysis proposed by Wolman and Miller (1960) assumes independence of successive events, but studies in a variety of areas indicate that major floods may change the quantity of sediment available for transport (Brown and Ritter 1971) and channel conditions (Ritter 1974, Baker 1977) encountered by subsequent events.

"Geomorphic recovery" after major disturbances is an essential part of judging effects of episodic events on sediment yield, but it is a concept interpreted in many ways. Wolman and Gerson (1980) discuss channel recovery in terms of return to predisturbance geometry, but judge recovery of landslide scars on the basis of degree of revegetation. Geomorphic recovery from a sediment-routing standpoint could be viewed as the refilling of storage sites and their readiness to fail again. The rate of such recovery for landslide scars varies greatly depending on the scale of the feature. Massive slope failures of essentially entire, first-order drainage basins (Kelsey, this volume) recover by rock weathering and soil formation. A much smaller proportion of a drainage basin fails in hollow/swale sites. Hollow/swale sites are recharged by transport of colluvium from adjacent areas, so their recovery is likely to be more rapid than that of the more massive failures where recharge is limited by weathering rate. Over several episodes of sliding, however, weathering must be the rate-limiting process in both systems.

Clearly the long-term significance of episodic events in sediment budgets and routing systems is difficult to quantify because the meager record of past events is dominated by the most recent one or two and the longer term sequence and timing of past events is important. Here again, the geomorphologist may have to rely on the tools of the dendrochronologist and Quaternary stratigrapher to place limits on the timing of past events.

## Biotic Factors in Sediment Routing

Biological parts of landscape systems contribute important components of sediment, act as agents of sediment transfer, form sediment-storage structures, and record forest and geomorphic history. Biological influences on geomorphology are particularly well developed in forest vegetation--reflecting, in part, the massive size and relatively slow decomposition rate of woody material in many forest environments.

The role of organic matter as a soil component is better understood than its role as sediment. Organic matter in soil is an essential part of both nutrient cycling and mineral weathering, which strongly influences soil stability. Sediment-transport studies by hydrologists and geomorphologists typically disregard the importance of organic matter in sediment both in deposits and in transit, but ecological research on drainage basins has emphasized the importance of streams in exporting organic matter from ecosystems (Arnett 1978). Organic matter may comprise a large proportion of sediment in transport, thus potentially complicating sediment sampling and confounding interpretation of the data (Arnett 1978). Sedimentologists have long been interested in the alteration of sediment characteristics during transport through a drainage basin, but interest among geomorphologists in extending these concepts to soil-sediment relations is rather new (Dietrich and Dunne 1978). Aquatic ecologists are becoming increasingly interested in the parallel issue of variation in the quantity and type of organic matter transported or temporarily stored throughout a drainage network (Naiman and Sedell 1979, 1980). Interactions between dissolved and fine particulate organic and inorganic matter (Jackson et al. 1978) present problems for sampling, distinguishing, and interpreting dissolved and suspended sediment yield from a sediment-routing standpoint. These interactions affect the fate and persistence of pollutants in ecosystems.

Plants and animals also affect soil and sediment movement and temporary storage in a variety of ways, many of which are described in papers in this volume. Effects of fauna and flora on individual erosion processes have been quantified in some detail, ranging from Darwin's (1881) work on erosion by earthworms to recent studies of tree-root effects on the potential for shallow mass movements (O'Loughlin 1974, Ziemer 1981). Where vegetation decreases the effectiveness of sediment-transport processes, it enhances sediment storage and increases the residence time of sediment by dissipating the energy of sediment-transporting media and by holding sediment in place. Large woody debris in streams and on hillslopes and tree roots are examples of biological materials that retain sediment at temporary storage sites.

The multiple, cumulative effects of vegetation on sediment routing through small (less than 100 ha) drainage basins have been demonstrated by studies in both forested and disturbed conditions (Bormann et al. 1969, 1974; Fredriksen 1970; Swanson et al., 1982; and others).

Dendrochronology may also be an integral part of sediment-routing studies by placing limits on the date of an event, rate of a process, and residence time of material in storage (Alestalo 1971; Schroder 1978; Hupp and Sigafoos, this volume; Brown, this volume; and others). Furthermore, general aspects of vegetation history can be interpreted by dendrochronologic analysis of events, such as wind storms and wildfire, and by palynological analysis of vegetation response to change in climate. This knowledge affects extrapolation of sediment-budget information to periods longer than those covered by direct observational data.

Interest in these long-term interactions between biotic and geomorphic systems goes beyond basic, academic concerns, and forms a foundation for interpreting and predicting impacts of management activities on forest ecosystems and landscapes. The successional development of ecosystems after disturbance determines the pace of recovery of vegetative control of sediment movement and storage. Likens and Bilby (this volume), Swanson et al. (1982), and others have argued that analysis of geomorphic systems should be placed in the context of vegetative succession and disturbance history.

## Weathering

Study of weathering and its effect on availability of plant nutrients, soil development, and soil stratigraphy is advanced compared with knowledge of weathering as a regulator of sediment routing. Weathering affects the availability of material for transport and the types and rates of transport processes operating in an area (Dietrich and Dunne 1978). Geological material enters the sediment-routing system by weathering of bedrock, which makes it available for transport.

Dietrich and Dunne (1978) suggest that weathering is a critical rate-limiting factor in the long-term movement of sediment in many mountain environments. This may be particularly true in steeplands with shallow soils over competent bedrock; examples are the Oregon Coast Ranges (Dietrich and Dunne 1978) and the mountains of Hawaii (Scott and Street 1976). Weathering is less crucial in determining the availability of erodible material where primary sediment sources are deep soils, unconsolidated sediments, or tectonically shattered rock, such as recently glaciated terrain (Madej, this volume) and the tectonically active California Coast Ranges (Kelsey, this volume).

Once material is available for transport, the types and rates of movement depend strongly on soil depth and on physical properties of the material determined by parameters such as grain-size distribution and clay mineralogy (Dietrich and Dunne 1978). Dietrich et al. (this volume) argue that change in soil depth with refilling of "hollows" results in increasing susceptibility of the site to failure by additional debris sliding. Weathering processes and their interaction with biota alter soil cohesion, bulk density, and mechanical properties, consequently controlling the rates of virtually all hillslope transport processes.

Weathering changes material while it is in temporary storage at various sites within a drainage basin. The rates and types of weathering reactions may vary from one storage site to another, depending on characteristics of the local weathering environment, such as hydrology, temperature fluctuations, pH, and oxidation-reduction conditions. Glancy (1971) and others, for example, have noted the break up of pebbles of sedimentary rock on gravel-bar surfaces over a period of months. They suggest that this is a bar-surface phenomenon only, so stones buried at shallow depths within the bar would not undergo this partial conversion from bedrock to suspended-load particle sizes.

The residence time of material in some storage sites stretches to the time scale of significant weathering and soil-profile development. Workshop participants (Harden et al., this volume) argued that soil stratigraphic techniques could profitably be used to determine residence time of storage sites and sometimes to set limits on the time since the last mass movement at a site.

These few examples indicate that weathering studies have an important, but little used, place in sediment-routing research.

## Modeling of Sediment Budgets and Routing

Computer simulation of sediment routing holds great promise for aiding compilation of sediment budgets and for simulating sediment-routing systems in ways useful for predicting system change in response to disturbances. A simulation model provides a rigorous statement of a sediment-routing system and highlights the kind and quality of field data needed for prediction. Existing simulation models require much more development before they meet this promise, however.

Two types of models were discussed at the workshop: a model by Simons et al. based on physical processes and Rice's Monte Carlo simulation of sediment production in response to a long sequence of fires and rainstorms. Each approach has its benefits and limitations.

Limitations of the model described by Simons et al. and of similar models developed for agricultural lands include: lack of treatment of mass wasting processes that can dominate sediment transport in steep land; uncertainty about the accuracy of some components of the model, such as the use of equations developed for sediment transport in deep stream channels to estimate transport by sheetflow; and the need for calibration of the model against a set of field data to obtain several parameters of the equations. Calibrations include such physically ill-defined concepts as soil "detachment coefficients" for rainfall and overland flow. Finding a set of coefficients that produce a good fit between predicted and observed water and sediment discharge does not necessarily lead to understanding of what is actually happening in the landscape, or even of where most of the sediment originates in a heterogenous landscape. Nor do such fits promote confidence in predictions of the consequences of some disturbance by climate or land use. More field experiments need to be conducted and generalized so that model parameters can be estimated a priori and tested against a few measured outputs. Nevertheless, information organized in such models is useful for developing other models and conducting field experiments to refine them.

Rice proposes the application of Monte Carlo simulation to describe the response of an erosion-sedimentation system to random meteorological events that drive the sequence of fires and rainstorms and interactions among them. He questions the utility of process-based mathematical models because of the need for calibration. Particularly in a region where the sediment budget is strongly affected by random phenomena that vary greatly from year to year, the model should be calibrated against a large number of events covering the most important combinations of parameter values. Rice also points out, however, that in addition to frequently discussed difficulties with the structure of geophysical data, empirical-statistical models suffer the same drawback as process models; the instrumental record is unlikely to contain sufficient important events to include adequate combinations of the most effective factors.

The refinement of studies of sediment budgets requires a combination of: field monitoring of processes coupled with measurements of the controlling variables, so that physically based process models can be developed; field experiments under controlled conditions to extend the range of observations on which the process models are founded; and the development of deterministic models of processes and their linkages. These models can then be used in Monte Carlo simulations, as suggested by Rice. A precedent in hydrology is the recent work of Freeze (1980) on runoff processes.

## CONCLUSIONS

In this workshop, we took an interdisciplinary look at the state of knowledge on development and use of sediment budgets and routing studies for forest drainage basins and identified important directions for future research. Most analyses have considered channels as the major storage sites and budgets have included hillslope processes, changes in channel storage, and outflow by fluvial processes. Temporal scales range from one year to millenia, spatial scales from less than a hectare to tens of thousands of square kilometers. Objectives of current studies range from purely basic questions of how geologic materials move through drainage basins to analyses of impact of management practices on sedimentation and a variety of resources.

Central points identified and further research needs are:

- Sediment storage is an essential but poorly understood and poorly quantified component of sediment budgets or routing analyses.

- Our ability to conduct field studies and to develop computer simulation models of sediment transport processes is limited by our knowledge of mechanisms of transport and the geomorphic context in which they operate.

- Episodic processes dominate sediment transport in many steep terrains, but theory and quantification of these processes are not well developed, particularly the interactions between successive events.

- Biota play a variety of essential roles in the production, transport, and storage of sediment, but knowledge of biological functions is poorly integrated into quantitative analysis of sediment budgets and routing.

- Weathering affects the availability and properties of sediment, but because significant weathering commonly occurs over long periods relative to traditional studies of processes, weathering has been little studied or used in sediment budget and routing studies.

- Computer simulation modeling is useful for predicting system behavior and for integrating concepts, process mechanisms, and field data. Modeling efforts, however, have not yet dealt with the types of storage sites and erosion processes that dominate in many forested mountain lands.

Advance of knowledge in each of these areas would be facilitated by improving theoretical analyses of processes, accumulation of long-term data sets, and more standardization of procedures and terminology. Economic considerations, in part, are leading to declining support by science managers for collecting long-term data sets, although scientists at the workshop were unanimous in their support of the need for such records. Computer simulation modeling, although a useful way of maximizing the value of field data, does not by itself provide useful surrogate records in geomorphic systems where infrequent events dominate sediment transport and where knowledge of interactions between successive events is weak.

Standardization of procedures and terminology in field and modeling efforts would facilitate future efforts to compare and contrast budgets and routing in diverse geomorphic systems. Efforts to standardize, however, must be tempered by the need to express adequately the sediment routing characteristics of particular terrain, climate, and vegetation types. The inability of the discussion group on use of flow charts in sediment routing studies to develop a single flow chart common to many landscapes reflects the difficulty of balancing details of local knowledge with the general need of achieving a basis for comparing diverse systems.

Use of sediment budget and routing analysis of drainage basins is in its infancy. Continued application of these methods in a variety of environments in studies with diverse objectives attests to increasing recognition of the value of sediment budgets and routing studies.

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Sediment budgets quantify the transport and storage of soil and sediment in drainage basins or smaller landscape units. Studies of sediment routing deal with the overall movement of soil and sediment through a series of landscape units. The 14 papers and 5 summaries from discussion groups in this volume report results of sediment budget and routing studies conducted principally in forested drainage basins. Papers also deal with sediment routing studies using computer models, physical models, and field observations in nonforest environments.

This work emphasizes methods for judging the relative importance of sediment sources within a basin, the many roles of biological factors in sediment transport and storage, and the importance of recognizing changes of sediment storage within basins when interpreting sediment yield. Sediment budget and routing studies are important tools for both research scientists and land managers.

Keywords: Sedimentation, watershed management, sediment budget, drainage basins, geomorphology.

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# A Procedure for Analysis of Guyline Tension

Ward W. Carson, Jens E. Jorgensen,
Stephen E. Reutebuch, and William J. Bramwell

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## Authors

WARD W. CARSON was a research engineer with the Pacific Northwest Forest and Range Experiment Station at the time of this study. He is now a senior research fellow with the Production Forestry Division, Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand. JENS E. JORGENSEN is a professor with the Mechanical Engineering Department, College of Engineering, University of Washington, Seattle, Washington 98195. STEPHEN E. REUTEBUCH and WILLIAM J. BRAMWELL were research assistants with the College of Forest Resources, University of Washington, Seattle, at the time of this study. S.E. Reutebuch is now a research logging engineer with the Production Forestry Division, Forest Research Institute, New Zealand Forest Service, Rotorua, New Zealand. W.J. Bramwell is now a logging specialist with the USDA Forest Service, Pacific Northwest Region, Willamette National Forest, Eugene, Oregon.

## Abstract

Carson, Ward W.; Jorgensen, Jens E.; Reutebuch, Stephen E.; Bramwell, William J. A procedure for analysis of guyline tension. Gen. Tech. Rep. PNW-142. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 45 p.

Most cable logging operations use a spar held in place near the landing by a system of guylines and anchors. Safety and economic considerations require that overloads be avoided and that the spar remain stable. This paper presents a procedure and a computer program to estimate the guyline and anchor loads on a particular system configuration by a specific set of operating line tension loads. A brief description of the analytical model used for the computations is included. There are instructions on the use of the computer program, a description of the necessary outputs, and a program listing for those who wish to prepare the program for use on other computer facilities.

Keywords: Logging equipment engineering, cable skidding equipment, models, computer programs/programing.

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## Introduction

An important component of any cable logging system, once it is set in place for yarding, is the lift that can be provided to suspend the logs. The deflection available to the system is a measure of this lift and is usually provided by a spar tree or tower at the landing. Spars must be stabilized by a system of anchors and guylines capable of resisting the yarding loads. This paper describes the analytical model and a computer technique needed to analyze the guyline tension response to the yarding loads.

Both safety and economic considerations dictate that operators of cable systems be concerned about the proper anchoring of the spar. The upset or collapse of a spar results in economic losses and can also produce injury or loss of life. State safety records, however, show that such mishaps are common in the logging industry. The causes of these mishaps are generally traced to a guyline tension overload resulting in failure of an anchor, a guyline, or a spar. These overloads are often the result of a poor arrangement of guylines or anchors, or a lack of understanding of just how severely the system was loaded. Our objective in this analysis was to provide a means by which the relationships betweeen the tensions produced in a multiguyline system may be examined as a function of the loads applied to the tower by the operating lines.

When provided with the operating line tensions and the geometric arrangement of the anchor system, the computer program can calculate the loads in the guylines, anchors, and the spar itself. The model is applicable to the spar-guyline-anchor system shown in figure 1. This is the system generally used for high-lead, live skyline (often called shotgun or flyer) systems, or other skylines that employ more than two operating lines. The spars are usually made of steel and are free to pivot at their base, the latter being a requirement for proper application of this program.

The analytical and computational approach described can be used in most areas of forest engineering for: (1) determining anchor loads, (2) selecting stump anchors or placing artificial anchors if required, (3) training forest engineers in spar tower anchor layout, and (4) analyzing tail and support trees. In summary, this program provides a means for a case by case, numerical examination of the spar-guyline-anchor system loads caused by the forces encountered during logging.

## Analytical Model

The analysis and the computer algorithms were developed as a cooperative effort. Our first attempt to develop a program was based on an analytical model that represented the guylines of the system as linear springs and was reported by Bramwell (1977). In January 1977, a field test of a guyline anchor system was performed (Jorgensen and others 1977); the results of our linear spring model were found inadequate as an accurate predictor of guyline tensions, particularly when the system had low guyline pretensions. Therefore, a second program was developed based on a model that accounts for the influence of the changing catenary shape of the guylines (Reutebuch 1978). In addition, a more direct computational algorithm was developed to alleviate several instabilities that would occur in the original approach. The results of this model agreed well with our experiments. The program presented here is based on it. The basic elements of this analysis will give the user an appreciation for the applicability of the program.

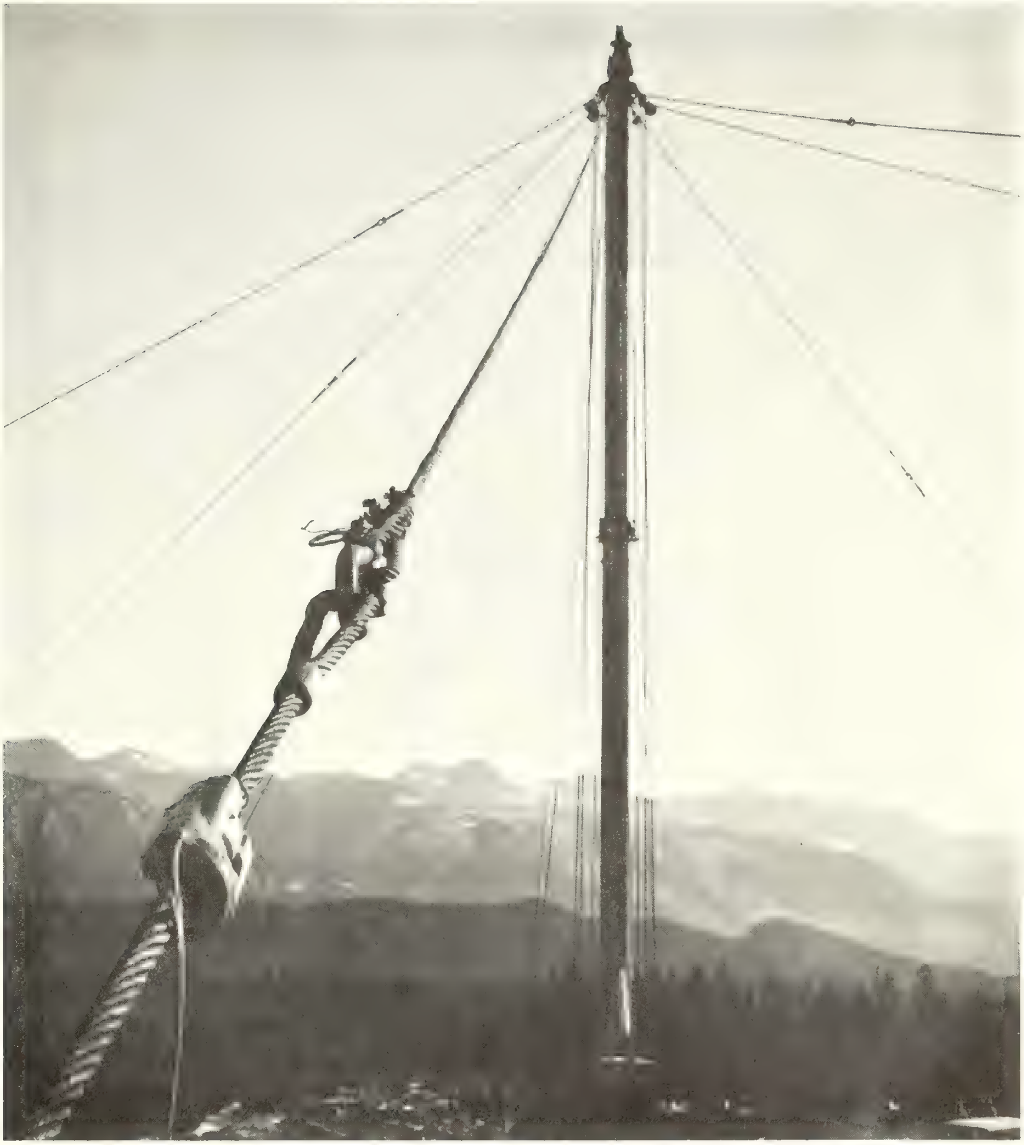

Figure 1.—Guylines supporting a steel logging tower.

## Coordinate System and System of Units

A right-handed rectangular coordinate system with its origin at the tower base (fig. 2A) is used in this analysis.

The location of each anchor point is described by the azimuth direction, distance, and elevation relative to the tower (spar) base. The direction of pull by an operating line is given by its angular orientation in terms of the azimuth and elevation angle. The latter is defined with respect to the horizontal base plane (X-Y plane). The traditional survey method of measuring azimuth is in a clockwise direction. In this analysis, azimuth 0° is alined with the positive X axis as shown in figure 2B.

The British Engineering System (Halliday and Resnik 1961) of units is used throughout this analysis and in the computer program.

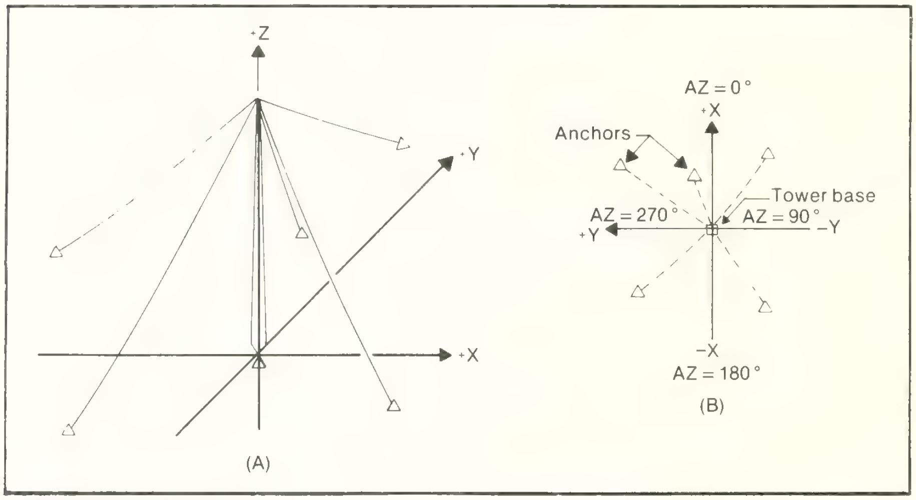

Figure 2.—Tower system coordinate system.

## Static Equilibrium of the Tower System

The operation of a yarding tower system can be divided into two phases: (1) the setup phase in which yarding is not underway and (2) the yarding phase in which yarding is underway. In both these phases, the tower system is considered to be in static equilibrium.

If we assume that the operating lines and the guylines are attached to a common point at the top of the tower, the tower system can be modeled as a system of concurrent forces in space acting through the top of the tower as shown in figure 3.

Such a system of concurrent forces is in static equilibrium when the sum of the moments (M) about any given point is equal to zero. The resultant, R, of the forces at the tower top equals zero:

$$\Sigma M_{base} = Rh = 0,$$

where h = tower height;
therefore, R = 0.

It follows that the sum of the components of the concurrent forces F (that is, the guyline tensions, $T_i$ ; the operating line tensions, $f_j$ ; and the compressional force in the tower, C) must be equal to zero:

$$\Sigma F_x = \Sigma T_{xi} + \Sigma f_{xj} + C_x = 0. \qquad (1)$$

$$\Sigma F_y = \Sigma T_{yi} + \Sigma f_{yj} + C_y = 0. \qquad (2)$$

$$\Sigma F_z = \Sigma T_{zi} + \Sigma f_{zj} + C_z = 0. \qquad (3)$$

The tower system is in static equilibrium when equations (1), (2), and (3) are satisfied.

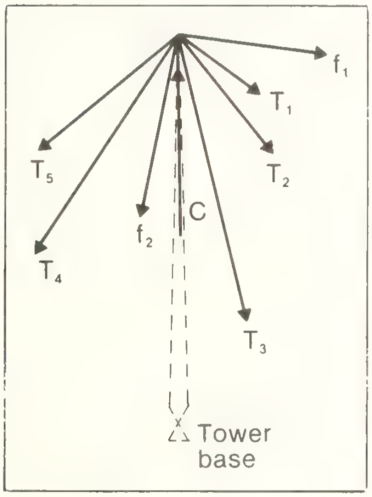

Figure 3.—Free body diagram of tower top.

## Analytical Description of the Guyline

In this section, the properties of a guyline as a structural member in a yarding tower system are presented so that the guyline tensions needed to solve equations (1), (2), and (3) may be calculated.

**Tension stretch relationship of wire rope.**—Wire rope is used for the guyline material. Within its elastic limits, up to 65 percent of the cable breaking strength (Broderick & Bascom Rope Company 1966), the stretch in a guyline, $\Delta S$, caused by a tension, T, obeys Hook's law:[1]

$$\Delta S = \frac{T\ell}{AE} ,$$

$$\text{or } \Delta S = \frac{T}{k} ;$$

$$\text{where } k = \frac{AE}{\ell} ,$$

$\ell$ = wire rope length,
A = metallic cross-sectional area of wire rope,
E = modulus of elasticity of wire rope material, and
k = guyline coefficient of stretch.

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[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

When the tension in a guyline exceeds its elastic limits, cable stretch cannot be accurately computed using the relationship given above. Therefore, if a guyline is tensioned beyond the elastic limit, the results of this analysis are invalid.

If we use the above relationships, the guyline stretched length, $S_i$, may be expressed in terms of the guyline unstretched length, $S_{oi}$, and its associated tension, $T_i$:

$$S_i = S_{oi} + T_i / k_i. \tag{4}$$

**Catenary description of the guyline.**—A guyline in a tower system is a cable evenly loaded along its length and hanging under its own weight. Such a cable assumes the shape of a catenary curve. An analytical description of the catenary curve and the formulation of various catenary problems commonly encountered in cable logging systems have been presented by Carson (1977).

Carson formulated the general catenary equations that relate guyline geometry, as shown in figure 4, to guyline length and tension. The stretched length of the ith guyline is given by the equation:

$$S_i = [Y_i^2 + (2\,m_i\ \sinh\,(d_i / 2\,m_i))^2]^{1/2} \tag{5}$$

The tension at the upper end of the guyline is given by the equation:[2]

$$T_i = w_i / 2(S_i\ \coth(d_i / 2\,m_i) + Y_i)\ ; \tag{6}$$

where $m_i$ is the catenary parameter and is equal to the horizontal component of tension, $H_i$, at any point along the guyline divided by the weight per foot of the guyline, $w_i$:

$$m_i = H_i / w_i\ .$$

Since the value of $H_i$ is not always known for a guyline, equations (5) and (6) are often transcendental and require an iterative solution technique.

## Geometric Compatability of the Tower System

Each guyline in the tower system has a stationary, rigid anchor at a known distance, $A_i$, from the base of the tower and a common anchor point at the top. To solve equations (5) and (6), the relative location of the tower top with respect to each stationary guyline anchor must be determined.

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[2] Unless otherwise stated, guyline tension refers to the tension in the guyline at the top of the tower.

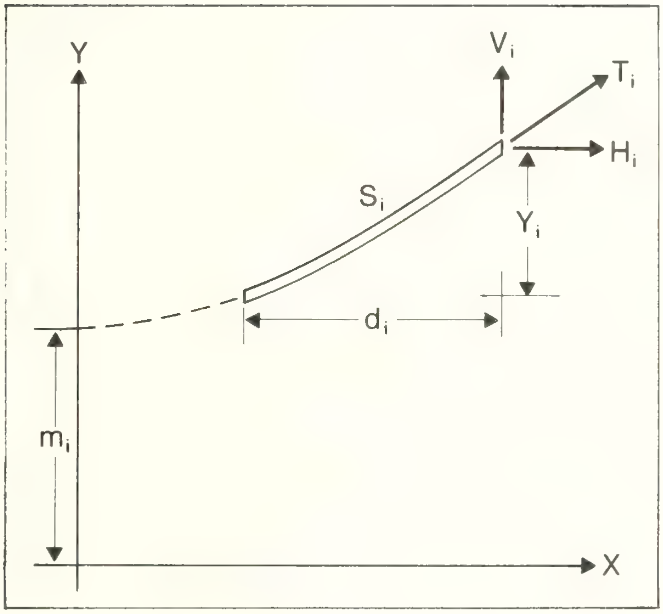

Figure 4.—Coordinate system and geometry for a single guyline.

All possible locations of the tower top lie on the surface of a sphere, with its center at the tower base and its radius equal to the tower height as shown in figure 5.

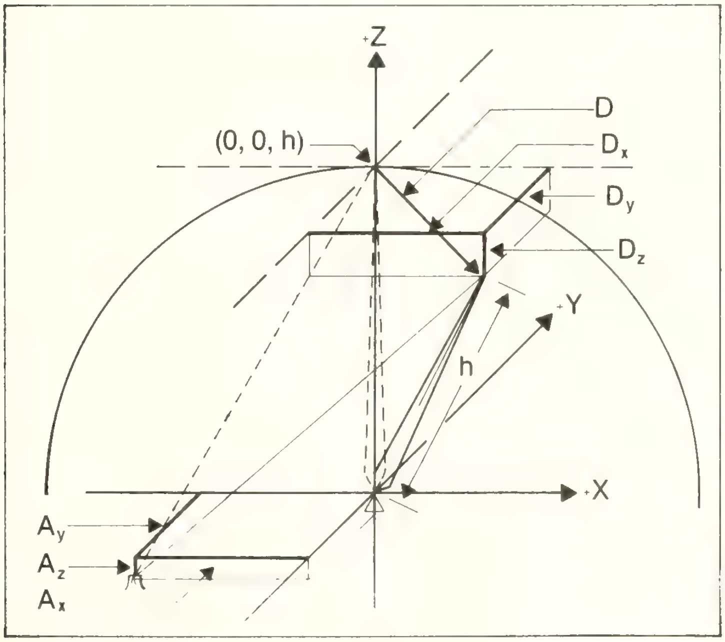

Figure 5.—Spherical surface of possible location of tower top.

Defining tower top displacement, D, as the distance from the point (0,0,h) to the actual location of the top of the tower (fig. 5), the equation of this sphere may be expressed in terms of tower height and tower top displacement:

$$h = [D_x^2 + D_y^2 + (h+D_z)^2]^{1/2} \tag{7}$$

The relative location ($D_i$, $Y_i$) of the tower top with respect to each anchor can then be expressed:

$$D_i = [(A_{xi} + D_x)^2 + (A_{Yi} + D_Y)^2]^{1/2}; \tag{8}$$

$$Y_i = -(A_{zi} - h - D_z); \tag{9}$$

where $A_i$ is the distance from the tower base to the ith anchor location.

## Computational Model of the Yarding Tower System

The mathematical relationships developed for the tower system are the equilibrium equations (1), (2), and (3); the cable stretch equation (4); the catenary relation equations (5) and (6); and the geometric compatibility relation equations (7), (8), and (9).

In this section, these components are used to construct a computational model of the tower system (fig. 6), which can be used to predict the static loads that develop in the guylines for a given tower loading.

The program is divided into two segments corresponding to the phases of the tower system, the setup phase and the yarding phase.

**Setup phase.**—As in the field, the computational model of the tower system must start with a setup phase in which the system geometry, equipment specifications, and initial operating line loads are specified. The model must then solve equations (1), (2), and (3) to find the guyline pretensions which put the system into equilibrium. There are generally four to eight unknown guyline pretensions and only the three equations of equilibrium; therefore, an iterative approach (Reutebuch 1978) must be used to solve these equations. As in the field, there is an infinite number of sets of pretensions that satisfy the equations of equilibrium for a given system geometry. The setup phase provides a means of determining a reasonable set of pretensions.

The pretensions that satisfy equations (1), (2), and (3) are then used in equation (5) to compute the stretched length of each guyline. Because the catenary parameter, m, is not known, an iterative method (Carson 1977) must be used to solve equation (5). The unstretched length of each guyline is then computed using the tension-stretch relationship given in equation (4). In the field, the guyline drums are locked in place by the end of the setup procedure; therefore, the unstretched guyline lengths, $S_{oi}$, are constant in the yarding phase of tower operation.

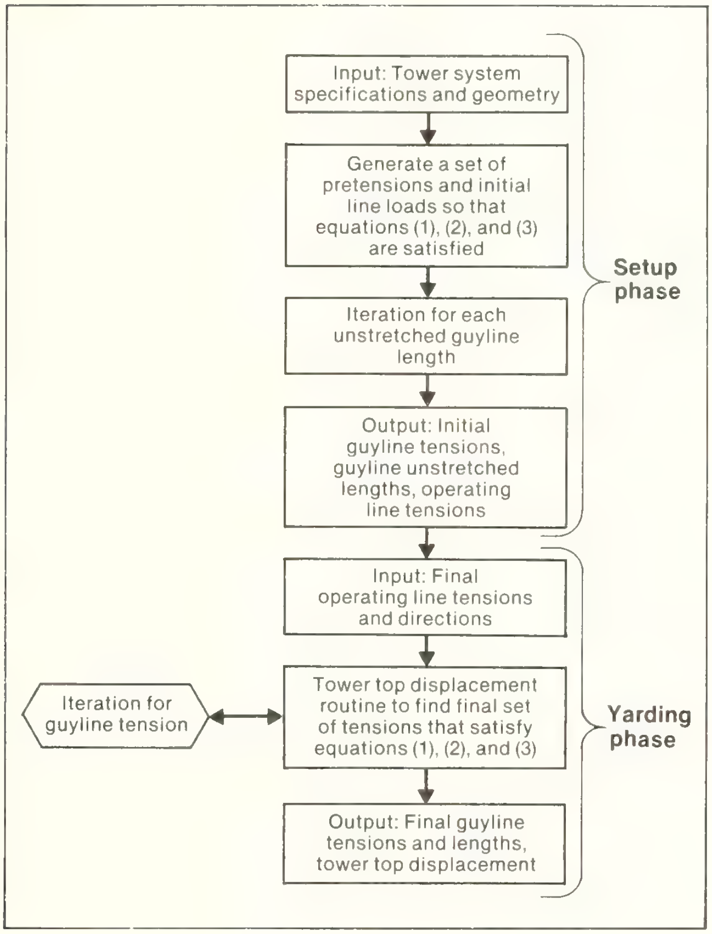
Input: Tower system specifications and geometry
Generate a set of pretensions and initial line loads so that equations (1), (2), and (3) are satisfied
Iteration for each unstretched guyline length
Output: Initial guyline tensions, guyline unstretched lengths, operating line tensions
Setup phase
Input: Final operating line tensions and directions
Iteration for guyline tension
Tower top displacement routine to find final set of tensions that satisfy equations (1), (2), and (3)
Output: Final guyline tensions and lengths, tower top displacement
Yarding phase

Figure 6.—Computational model of the yarding tower system.

**Yarding phase.**—The tower system is in a state of static equilibrium for the given initial tower system geometry. The final operating loads, $f_j'$, on the system are now introduced.[3] With these new line loads, equations (1), (2), and (3) are no longer satisfied; the system is no longer in equilibrium. New guyline tensions, $T_i'$, and a new tower compressional force, $C'$, must be found to satisfy the conditions of equilibrium:

$$\Sigma F_x' = \Sigma T_{xi}' + \Sigma f_{xj}' + C_x' = 0. \qquad (1A)$$
$$\Sigma F_y' = \Sigma T_{yi}' + \Sigma f_{yj}' + C_y' = 0. \qquad (2A)$$
$$\Sigma F_z' = \Sigma T_{zi}' + \Sigma f_{zj}' + C_z' = 0. \qquad (3A)$$

The action of the operating loads will cause the tower top displacement to change. An iterative technique is used, by successive trials of system geometries (Reutebuch 1978), that yields an associated set of guyline tensions, until equations (1A), (2A), and (3A) are satisfied and the system again is in static equilibrium.

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[3] These final operating loads can be assumed to be the yield point of the operating lines, or they may be computed by the "chain and board" method or one of several computational methods introduced in recent years.

In the displacement iteration routine, successive estimates of x and y components of tower top displacement, $D_x'$ and $D_y'$ are made and then used in equation (7) to solve for $D_z'$:

$$D_z' = (h^2 - D_x' - D_y'^2)^{1/2} - h. \qquad (7A)$$

With each trial of a tower top displacement, there is a new guyline geometry, $D_i$ and $Y_i$, which is used in equation (5) to solve for the stretched guyline length, $S_i'$. Equation (4) is then used to find the tension, $T_i'$, in each guyline, given the guyline's stretched and unstretched lengths:

$$T_i' = (S_i' - S_{oi})/k_i. \qquad (4A)$$

The iteration on tower top displacement continues until a set of guyline tensions that satisfies equations (1A), (2A), and (3A) is found. At this point, the problem for that specific set of operating loads is complete and all pertinent information is printed.

## The Guyline Tension Analysis Program

### General Information

The program is written in the American Standard Code for Information Interchange (ASCII) BASIC language common to many computer systems. It was developed on a Hewlett-Packard 9845 desk-top calculator/plotter system at the Pacific Northwest Forest and Range Experiment Station Forestry Sciences Laboratory, Seattle, Washington. A FORTRAN version currently running on the PDP-11/44 in the Mechanical Engineering Department at the University of Washington is also available from the university.

The program listed in appendix B is the version for the HP9845 system. This system must include the following minimum features:

- BASIC MODEL 9845 calculator with 62650 bytes of read/write memory.
- Additional read only memory graphics.
- Internal thermal page printer.
- Dual inboard tape cartridge drives.

Although the program was prepared on a particular computer system and some familiarity with the mechanics of its operation is presumed, it is not limited to this system. The ASCII BASIC language is a common computer code, and the program can be executed on many other computers.

### Using the Program

To produce a program that could be used without complicated instructions, we used "visual prompters." These are questions or other printed messages to prompt the user to input the necessary information. These prompters are described in table 1.

The mechanics of program execution is best described by a specific example that allows the user to work through the program at least once. The user can treat other examples as variations of the one presented here.

**Table 1—Description of inputs for guyline tension analysis program**

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| NEW SETTING (Y/N)? | Y | Note: Data could be read from a previously stored data file. |
| SETTING NAME? | SNOQUALMIE | Assigns a name for output identification. |
| TOWER HEIGHT? | 106 | Height of spar from pinned base to guyline circle in feet (fig. 7). |
| DISTANCE FROM THE GUYLINE DRUMS TO THE TOWER TOP? | 100 | Distance from guyline circle to guyline drums in feet. |
| ELEVATION AT TOWER BASE? | 1968 | The elevation of the tower pivot or pin joint. |
| NUMBER OF POSSIBLE ANCHORS (UP TO 12)? | 10 | The number of stumps or artificial anchors being considered for guyline anchors. |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 1? | 193, 193, 1954 | These entries describe the anchor locations with respect to the base of the tower. They are, respectively, the azimuth, the horizontal distance from the tower to anchor, and the elevation of the anchor point. |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 2? | 248, 365, 1996 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 3? | 304, 193, 1988 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 4? | 332, 191, 1980 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 5? | 002, 162, 1962 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 6? | 034, 194, 1943 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 7? | 081, 218, 1894 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 8? | 117, 232, 1902 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 9? | 124, 196, 1921 | |
| AZIMUTH, HORIZONTAL DISTANCE, ELEVATION FOR ANCHOR 10? | 141, 227, 1919 | |

Table 1—Description of inputs for guyline tension analysis program (continued)

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| PLOT OF ALL POSSIBLE ANCHORS (Y/N)? | Y | Provides a plot of all possible anchors (fig. 8). |
| DO YOU WANT TO STORE SETTING (Y/N)? | Y | Setting stored on tape. Printed record shown in table 2. |
| FILE NAME (UP TO 6 CHARACTERS) | SNOQUL | Name of file on left tape in which setting is stored for later use. |
| INITIAL TOWER LEAN, ANGLE, AZ? | 0,0 | Inputs the angle from vertical and the direction (azimuth) in which the tower is initially leaning. |
| SAME DIAMETER FOR ALL GUYLINES (Y/N)? | Y | Provides an opportunity to input guylines of different diameters. |
| DIAMETER OF GUYLINES? | 1.375 | Inputs the diameter of guylines, in inches. |
| SELECT UP TO 8 ANCHORS | pause | |
| GUYLINE #1 - ANCHOR #? | 1 | Indicates that guyline 1 will be attached to anchor 1. |
| GUYLINE #2 - ANCHOR #? | 2 | Indicates that guyline 2 will be be atached to anchor 2, etc. |
| GUYLINE #3 - ANCHOR #? | 3 | |
| GUYLINE #4 - ANCHOR #? | 4 | |
| GUYLINE #5 - ANCHOR #? | 6 | |
| GUYLINE #6 - ANCHOR #? | 7 | |
| GUYLINE #7 - ANCHOR #? | 9 | Guyline 7 attached to anchor 9. |
| GUYLINE #8 - ANCHOR #? | 0 | Indicates that there are no more guylines. |
| GUYLINE CABLE FACTOR OF SAFETY? | 3 | Inputs the factor of safety, which is to be used to determine the wire rope working tension. |
| SAME PRETENSION FOR ALL GUYLINES (Y/N)? | | Provides an opportunity to input a different pretension for each guyline. |
| DESIRED PRETENSION IN GUYLINES? | 6000 | Inputs a base guyline pretension for all guylines, which will then be adjusted until system is in static equilibrium. |

Table 1—Description of inputs for guyline tension analysis program (continued)

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS? | 319 | Azimuth from the tower base to the operating line drums. |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 0 | Indicates that operating lines are slack when system is pretensioned. |
|  | pause | Program execution. The initial guyline tension is displayed on screen. |
| ARE PRETENSIONS SATISFACTORY? | Y | Provides an opportunity to try a different pretension arrangement. |
| SETUP NUMBER? | 1 | For output label. |
| DO YOU WANT A PLOT? | Y | Provides a plot of the system in its initial loaded condition (fig. 9). |
| RUN NAME OR NUMBER (UP TO 25 CHARACTERS) | 1 | Inputs the name or number with which the run will be labeled. |
|  |  | The initial guyline tension data are printed. See table 3. Program enters the yarding phase. |
| AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS? | 319 | Described earlier. |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 100000 | Inputs the tension in operating line number 1 (skyline to carriage). |
| OPERATING LINE ANGLE FROM THE HORIZONTAL (DEG.)? | 20 | Inputs the angle from the horizon to operating line number 1 (positive for downhill). |
| AZIMUTH OF OPERATING LINE LEAD (DEG.)? | 139 | Inputs the direction to the carriage from top to tower (skyline lead). |
| DISTANCE FROM TOWER BASE TO OPERATING LINE DRUM 1? | 10 | Inputs the distance (feet) from the tower to the operating line drum number 1. |

**Table 1—Description of inputs for guyline tension analysis program (continued)**

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 30000 | Inputs the tension in operating line number 2 (main line from tower top to carriage). |
| OPERATING LINE ANGLE FROM THE HORIZONTAL (DEG)? | 25 | Inputs the angle from the horizon to operating line number 2. |
| AZIMUTH OF OPERATING LINE LEAD (DEG)? | 139 | Inputs the direction to the carriage from top of tower (main line lead). |
| DISTANCE FROM TOWER BASE TO OPERATING LINE DRUM 2? | 15 | Inputs the distance (feet) from tower base to the operating line drum number 2. |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 0 | Indicates all operating lines have been input. |
|  | pause | Computer will go into solution procedure. Periodically it will flash the iteration number on the screen. |
|  | 1 | Start iterations. |
|  | • |  |
|  | • |  |
|  | • |  |
|  | 8 | Total iterations. |
| DO YOU WANT A PLOT? | Y | Provides a plot of the system in its final loaded condition (fig. 10 and table 4). |
| 1 = NEW LOAD |  | Provides menu. |
| 2 = NEW PRETENSIONS |  |  |
| 3 = NEW ANCHOR ARRANGEMENT |  |  |
| 4 = STOP |  |  |
| CHOOSE ONE OF THE ABOVE (1-4)? | 2 | New final operating line loads, new guyline pretensions, or a new anchor arrangement can be tried by entering the appropriate number. In this case, a new set of pretensions is tried. |

Table 1—Description of inputs for guyline tension analysis program (continued)

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| SAME PRETENSIONS FOR ALL GUYLINES (Y/N)? | N | Described earlier. |
| DESIRED PRETENSION IN GUYLINE 1 F/V? | 5500 | Inputs desired pretension in guyline 1. |
| ? | V | Indicates that pretension can be adjusted while balancing system (guyline tension variable). |
| DESIRED PRETENSION IN GUYLINE 2 F/V? | 4000 | Same as above. |
| ? | V | |
| DESIRED PRETENSION IN GUYLINE 3 F/V? | 4000 | Same as above. |
| ? | V | |
| DESIRED PRETENSION IN GUYLINE 4 F/V? | 4000 | Same as above. |
| ? | F | Indicates that pretension will not be adjusted while balancing system (guyline tension fixed). |
| DESIRED PRETENSION IN GUYLINE 5 F/V? | 9000 | Same as above. |
| ? | V | |
| DESIRED PRETENSION IN GUYLINE 6 F/V? | 12000 | Same as above. |
| ? | V | |
| DESIRED PRETENSION IN GUYLINE 7 F/V? | 4000 | Same as above. |
| ? | V | |
| AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS? | 319 | |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 0 | Described earlier. |

**Table 1—Description of inputs for guyline tension analysis program (continued)**

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
|  | pause | Iterations as described above. Iteration numbers will flash on display. |
| ARE PRETENSIONS SATISFACTORY? | Y |  |
| SETUP NUMBER? | 1 | For labeling output. |
| DO YOU WANT A PLOT? | Y | See figure 11 and table 5. |
| RUN NAME OR NUMBER UP TO 25 CHARACTERS? | 2 |  |
| AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS? | 319 | Described earlier. |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 100000 | Described earlier. |
| OPERATING LINE ANGLE FROM THE HORIZONTAL (DEG.)? | 20 |  |
| AZIMUTH OF OPERATING LINE LEAD (DEG.)? | 139 |  |
| DISTANCE FROM TOWER BASE TO OPERATING LINE DRUM 1? | 10 |  |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 0 | Indicates all operating lines have been input. |
|  | pause | Iterations as described above. Iteration numbers will flash on display. |
|  | 1<br>•<br>•<br>• |  |
|  | 9 | Total iterations. |
| DO YOU WANT A PLOT? | Y | See figure 12 and table 6. |
| 1 = NEW LOAD<br>2 = NEW PRETENSIONS<br>3 = NEW ANCHOR ARRANGEMENT<br>4 = STOP |  |  |

**Table 1—Description of inputs for guyline tension analysis program (continued)**

| VISUAL PROMPTER | KEYBOARD RESPONSE | DESCRIPTION |
|---|---|---|
| CHOOSE ONE OF THE ABOVE (1-4)? | 1 | New final operating line loads will be tried with the same set of anchors and pretensions. |
| RUN NAME OR NUMBER (UP TO 25 CHARACTERS)? | 3 | |
| AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS? | 319 | |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 200000 | |
| OPERATING LINE ANGLE FROM THE HORIZONTAL (DEG.)? | 20 | |
| AZIMUTH OF OPERATING LINE LEAD (DEG.)? | 0 | |
| DISTANCE FROM TOWER BASE TO OPERATING LINE DRUM 1? | 15 | |
| TENSION IN THE OPERATING LINE AT TOWER TOP (LB)? | 0 | |
| | pause | Iterations as described above. Iteration number will flash on display. |
| | 1<br>•<br>•<br>• | |
| | 10 | Total iterations. |
| DO YOU WANT A PLOT? | Y | Described earlier (fig. 13 and table 7). |
| 1 = NEW LOAD<br>2 = NEW PRETENSIONS<br>3 = NEW ANCHOR ARRANGEMENT<br>4 = STOP | 4 | Program stops. If an opportunity to try a new guyline geometry and tower lean is desired, input "3". |

**Input.**—The input necessary to this program is explained in the "Description" column of table 1. The remarks in this column explain what an operator does in response to the input requests that appear under the "Visual Prompter" column. The "Keyboard Response" column shows the input necessary for the specific example presented. Figure 7 describes the terminology used.

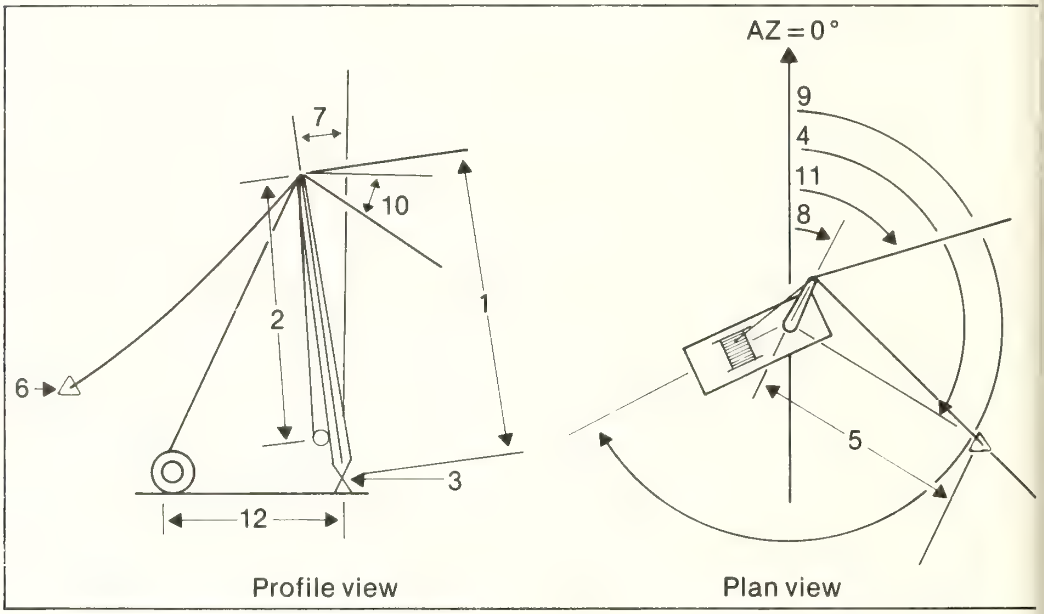


Figure 7. — Geometric inputs required for program use:

(1) tower height
(2) distance from guyline drums to tower top
(3) elevation at tower base
(4) azimuth from tower base to anchor
(5) horizontal distance from tower base to anchor
(6) elevation of anchor
(7) angle of tower lean (a positive value)
(8) azimuth of tower lean
(9) azimuth from tower base to tower operating line drums
(10) angle operating line from horizontal at tower top (positive for downhill, negative for uphill)
(11) azimuth of pull of operating line
(12) horizontal distance from tower base to operating line drum

## Description of Program Output

The output of the program provides the user with an analysis of the force-tension distribution that can be expected in the tower. Provided are the guyline angles, tensions and lengths, tower compression, and tower top displacement for whatever range of operating line arrangements the operator wants to examine. Both printed and plotted output are produced. Tables 2 to 7 show the text portion of the output produced when the example given in table 1 is run.

The printed output, like the model itself, is divided into two sections. Table 2 describes the setting. Table 3 describes the anchors chosen and the pretensions selected for the guylines. Table 3 also provides a summary of the force-tension components acting through the tower top at the end of the setup phase of the program. The second segment of the printed output (table 4 for the first setting) is a summary of the force-tension distribution and the changes that have occurred because of the imposition of the final operating line loads on the tower system. If a computed guyline tension is greater than the working strength of the guyline cable as specified by the safety factor, the output is flagged so that overstresses can be easily identified. If stresses beyond the elastic limit are present, a statement to indicate this condition is also provided. Tables 5 to 7 show the output for the initial section and the final sections for the other examples treated in table 1.

**Table 2—Listing of possible anchor locations**

```
          SETTING--SNOQUALMIE

TOWER HEIGHT= 106 FEET.
DIST:  GUYLINE DRUMS TO TOWER TOP  100  FEET.
ELEVATION AT TOWER BASE= 1968 FEET.
NUMBER OF POSSIBLE ANCHORS= 10
       *POSSIBLE ANCHOR LOCATIONS+
NUMBER    AZIMUTH    DISTANCE    ELEVATION
    1        193       193.0       1954.0
    2        248       365.0       1996.0
    3        304       193.0       1988.0
    4        332       191.0       1980.0
    5          2       162.0       1962.0
    6         34       194.0       1943.0
    7         81       218.0       1894.0
    8        117       232.0       1902.0
    9        124       196.0       1921.0
   10        141       227.0       1919.0
```

Table 3—Anchor location selection and pretensioning of the guylines

```
GUYLINE      *SELECTED ANCHOR LOCATIONS*           *GUYLINE*
 NUMBER    AZIMUTH   DISTANCE   ELEVATION      DIAMETER   ANGLE
   1         193       193.0      1954.0         1.375      32
   2         248       365.0      1996.0         1.375      12
   3         304       193.0      1988.0         1.375      24
   4         332       191.0      1980.0         1.375      26
   5          34       194.0      1943.0         1.375      34
   6          81       218.0      1894.0         1.375      40
   7         124       196.0      1921.0         1.375      38
     GUYLINE CABLE FACTOR OF SAFETY IS  3


         ** INITIAL OPERATING LINE AND GUYLINE TENSIONS **


AZIMUTH: TOWER BASE TO OPER. LINE DRUMS=  319  DEGREES

OPERATING LINES               TENSION     ANGLE  AZIMUTH   DRUM DIST
OPER. LINES VECTOR RESULTANT        0         0        0

GUYLINE          *PRETENSIONS*               *INITIAL LENGTHS*
NUMBER        INPUT       BALANCED       STRETCHED    UNSTRETCHED
   1           6000         6078           227.39         227.23
   2           6000         6078           373.97         373.74
   3           6000         4584           211.50         211.39
   4           6000         4584           213.08         212.97
   5           6000         5752           234.24         234.09
   6           6000         5752           282.94         282.77
   7           6000         7627           248.74         248.53
INITIAL TOWER TOP DEFLECTION: DIST, AZ       0.00       0
INITIAL TOWER COMPRESSION    60398  POUNDS
```

**Table 4—Final guyline tensions for setup 1, run 1**

```
   FINAL OPERATING LINE TENSIONS FOR SETUP #  1  RUN--1


AZIMUTH: TOWER BASE TO OPER. LINE DRUMS=  319  DEGREES

OPERATING LINES               TENSION     ANGLE  AZIMUTH   DRUM DIST
    OPER. LINE 1               100000       20      139       10
    OPER. LINE 2                30000       25      139       15
OPER. LINES VECTOR RESULTANT   206388       59      139

GUYLINE       *STRETCHED LENGTHS*           *GUYLINE TENSIONS*
 NUMBER   INITIAL    FINAL    CHANGE    INITIAL    FINAL    CHANGE
   1       227.39   227.29      -.10      6078     2385     -3693
   2       373.97   374.14       .17      6078    10606      4527
   3       211.50   212.98      1.48      4584    62992     58408
   4       213.08   214.52      1.43      4584    60955     56371
   5       234.24   234.46       .22      5752    14027      8276
   6       282.94   282.86      -.09      5752     2995     -2757
   7       248.74   248.58      -.16      7627     2158     -5469

UNBALANCED X-FORCE=-375    UNBALANCED Y-FORCE= 32
FINAL TOWER DEFLECTION: DIST, AZ            1.90    137
FINAL TOWER COMPRESSION  398997  POUNDS
NUMBER OF ITERATIONS= 8
```

**Table 5—New pretension selection for anchor setup 1**

```
         ** INITIAL OPERATING LINE AND GUYLINE TENSIONS **


AZIMUTH: TOWER BASE TO OPER. LINE DRUMS=  319  DEGREES

OPERATING LINES               TENSION     ANGLE  AZIMUTH   DRUM DIST
OPER. LINES VECTOR RESULTANT        0        0        0

GUYLINE          *PRETENSIONS*              *INITIAL LENGTHS*
NUMBER        INPUT       BALANCED      STRETCHED    UNSTRETCHED
   1           5500         7652          227.34        227.14
   2           4000         5565          374.11        373.91
   3           4000         3730          211.61        211.52
   4           4000         4000          213.15        213.05
   5           9000         5761          234.24        234.08
   6          12000         7682          282.84        282.61
   7           4000         3821          249.04        248.94
INITIAL TOWER TOP DEFLECTION: DIST, AZ        0.00      0
INITIAL TOWER COMPRESSION    57166  POUNDS
```

**Table 6—Final guyline tensions for setup 1, run 2**

```
   FINAL OPERATING LINE TENSIONS FOR SETUP #  1  RUN--2


AZIMUTH: TOWER BASE TO OPER. LINE DRUMS=  319  DEGREES

OPERATING LINES               TENSION     ANGLE  AZIMUTH   DRUM DIST
    OPER. LINE 1               100000       20      139       10
OPER. LINES VECTOR RESULTANT   158256       58      139

GUYLINE       *STRETCHED LENGTHS*          *GUYLINE TENSIONS*
 NUMBER   INITIAL    FINAL    CHANGE    INITIAL    FINAL    CHANGE
   1       227.34   227.21      -.13      7652      2732     -4920
   2       374.11   374.23       .12      5565      8670      3105
   3       211.61   212.78      1.17      3730     49771     46041
   4       213.15   214.29      1.14      4000     48903     44903
   5       234.24   234.38       .14      5761     11044      5282
   6       282.84   282.70      -.13      7682      3354     -4328
   7       249.04   248.99      -.05      3821      2031     -1790

UNBALANCED X-FORCE= 138    UNBALANCED Y-FORCE= 343
FINAL TOWER DEFLECTION: DIST, AZ            1.65    135
FINAL TOWER COMPRESSION  314675  POUNDS
NUMBER OF ITERATIONS= 9
```

**Table 7—Final guyline tensions for setup 1, run 3**

```
   FINAL OPERATING LINE TENSIONS FOR SETUP #  1  RUN--3


AZIMUTH: TOWER BASE TO OPER. LINE DRUMS=  319  DEGREES

OPERATING LINES               TENSION     ANGLE  AZIMUTH   DRUM DIST
    OPER. LINE 1               200000       20        0       15
OPER. LINES VECTOR RESULTANT   339177       52      355

GUYLINE       *STRETCHED LENGTHS*          *GUYLINE TENSIONS*
 NUMBER   INITIAL    FINAL    CHANGE    INITIAL    FINAL    CHANGE
   1       227.34   232.75      5.41      7652   210781!!! 203129
   2       374.11   374.84       .73      5565     24465     18900
   3       211.61   211.54      -.07      3730      1117     -2613
   4       213.15   213.07      -.08      4000      1006     -2994
   5       234.24   234.11      -.12      5761      1287     -4475
   6       282.84   282.81      -.02      7682      6969      -713
   7       249.04   252.38      3.35      3821   121860!!! 118039
!!!-GUYLINE WORKING LOAD EXCEEDED WITH SAFETY FACTOR OF  3
ELASTIC LIMIT OF CABLE EXCEEDED--THIS LOADING IS BEYOND THE RANGE OF THE MODEL

UNBALANCED X-FORCE= 10    UNBALANCED Y-FORCE=-83
FINAL TOWER DEFLECTION: DIST, AZ            7.08    351
FINAL TOWER COMPRESSION  828323  POUNDS
NUMBER OF ITERATIONS= 10
```

Three plan view plots of the tower setting are provided to aid the user in visualizing the anchor arrangement and operating line loads. The first plot of all possible anchors (fig. 8) is provided so the user can decide which combination of anchors to select. The next plot (figs. 9 and 11) provides a visual display of the tower system in the particular trial setup showing the initial tension distribution when the tower is unloaded. The tower top is at the intersection of the guylines. The final plot (figs. 10, 12, or 13) provides the user with a visual display of the tower system after final operating line loads have been imposed on the tower top. The resultant of the final operating line loads is represented on the plot by a dashed line terminated by an "R". The magnitude (MAG), angle, and azimuth (AZ) of the resultant are also listed. These plots allow the operator to quickly spot guylines with excessive tensions or poor distributions.

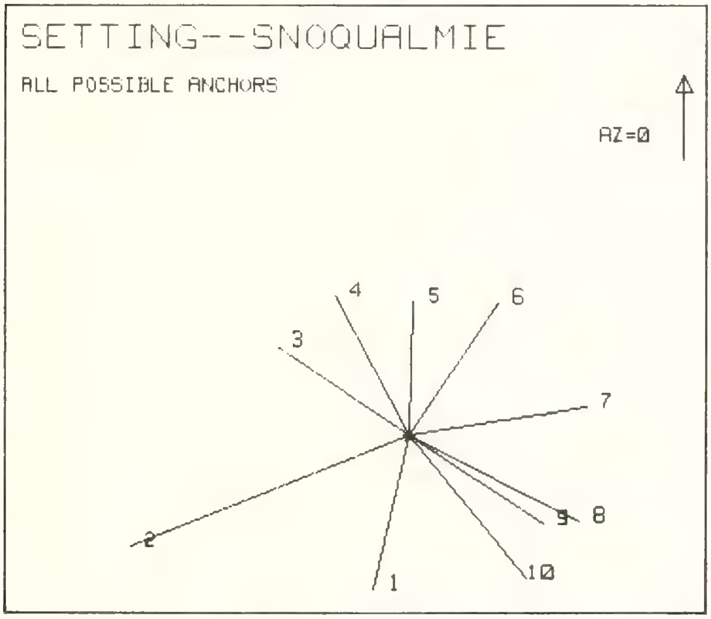


Figure 8.—Setting, Snoqualmie, all possible anchors.

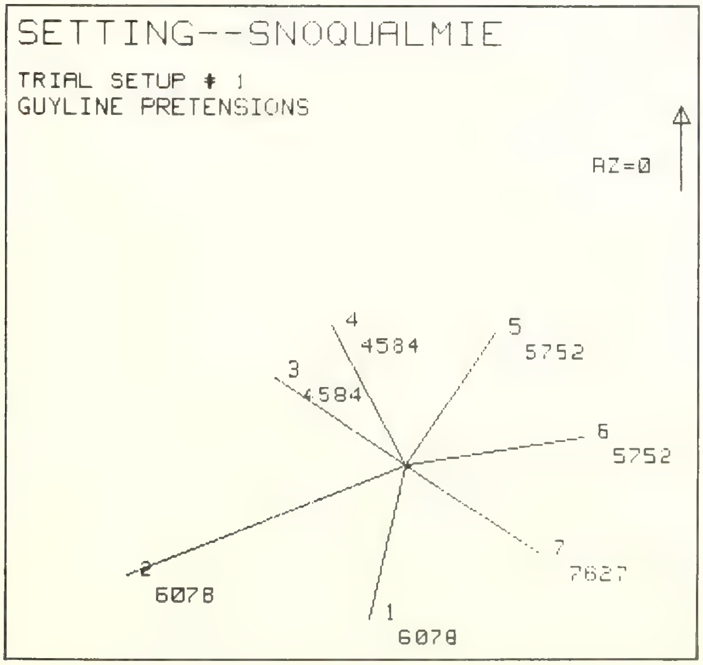


Figure 9.—Setting, Snoqualmie, guyline pretensions.

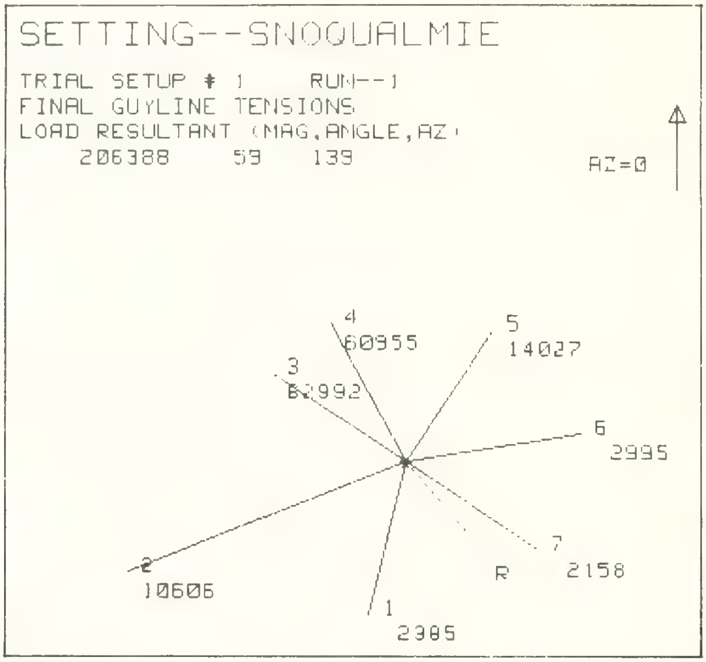


Figure 10.—Setting, Snoqualmie, final guyline tensions, run 1.

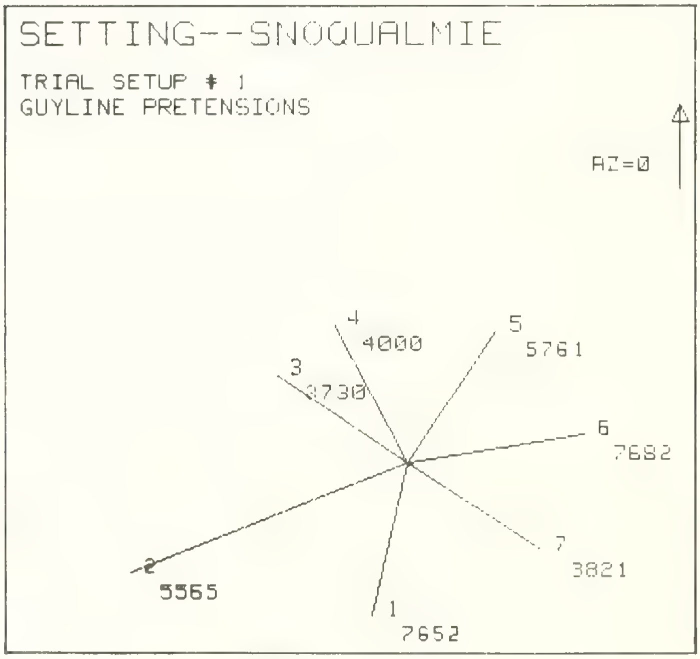
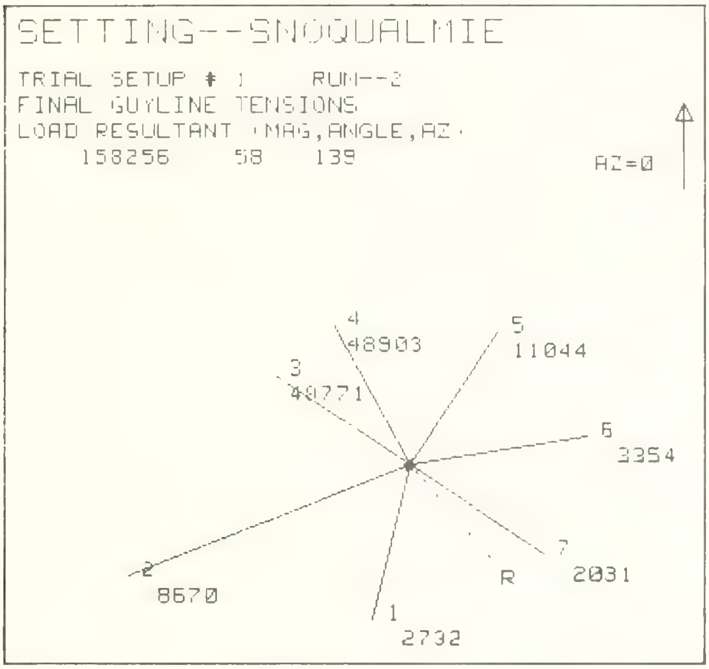
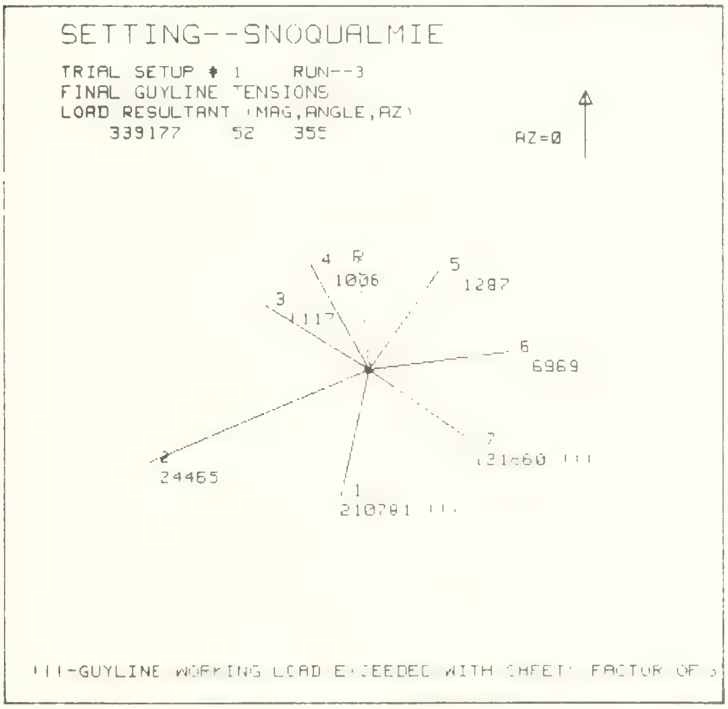


Figure 11.—Setting Snoqualmie, guyline tensions revised.



```
SETTING--SNOQUALMIE
TRIAL SETUP # 1     RUN--2
FINAL GUYLINE TENSIONS
LOAD RESULTANT (MAG,ANGLE,AZ)
     158256     58    139
```

Figure 12.—Setting Snoqualmie, final guyline tensions, run 2.



```
SETTING--SNOQUALMIE
TRIAL SETUP # 1     RUN--3
FINAL GUYLINE TENSIONS
LOAD RESULTANT (MAG,ANGLE,AZ)
     339177     52    355
```

```
!!!-GUYLINE WORKING LOAD EXCEEDED WITH SAFETY FACTOR OF 3
```

Figure 13.—Setting Snoqualmie, final guyline tensions, run 3.

## Limitations

This program is based on a static analysis of a logging system tower held in position by a set of cable guylines. Several assumptions were required to define the system configuration and its mode of operation. These assumptions restrict the application of the program.

To gain a full appreciation of the limitations of this program, a user should be familiar with the analytical model on which it is based. A more complete description is given by Reutebuch (1978). Some obvious limitations are listed and discussed here.

1. The tower is a weightless, rigid member, free to pivot in any direction. The weight of the tower is ignored since it is presumed that other loads and tensions will make the tower weight insignificant by comparison. This assumption is necessary so the tower can be assumed to bear the compressive loads only.

2. Guyline and operating line loads are applied at a single point on the tower top. Minor variations from this arrangement are assumed to have an insignificant influence on the results.

3. Anchors are rigid. It is assumed that the guyline anchor motion will be negligible during loading in comparison with the top of the tower.

4. Guylines are considered to be 6 x 19 IWRC (Independent Wire Rope Core) class of wire rope, stretched linearly and hanging as catenaries. These assumptions were required to identify properties of the cable—such as ultimate strength, elastic modulus, and weight-to-size relationship. The assumption of linear stretch limits the application of this program to cases where the guylines are tensioned to less than 65 percent of breaking strength. The inelastic stretch of wire rope beyond this limit will make the results of this program invalid.

5. The effective direction of guyline forces is along the chord from the tower top to the respective anchor point. This assumption was made for convenience of computations. It does limit the program applications where they are being used to determine loadings for slack guylines, whose loading direction is of interest.

6. The guyline pretensions must be a reasonable representation of actual conditions. This limitation is important because the final solution for loaded guyline tensions is based on their initial pretensions. These pretensions may have a major influence and must be carefully selected.

7. Guylines are rigged from winches near the tower base, up through sleeves at the top, and out to attachment points at the anchors. The program is not applicable to towers rigged with two-part guylines where one end dead ends at the top of the tower.

## Metric Conversions

| *Multiply* | *by* | *to get metric equivalent in* |
|---|---|---|
| Length: | | |
| Inches | 25.4 | millimeters |
| Feet | 0.305 | meters |
| Force: | | |
| Pounds | 4.45 | newtons |

## Literature Cited

Bramwell, William J., III. A computer model for determination of tensions in cable logging guylines. Seattle: University of Washington; 1977. Thesis.

Broderick & Bascom Rope Company. Wire rope handbook. St. Louis, MO: Broderick & Bascom Rope Company; 1966: 99.

Carson, W. Analysis of the single cable segment. For. Sci. 23(2): 238-252; 1977.

Halliday, David; Resnik, David. Physics for students of sciences and engineering. Combined edition. John Wiley & Sons, Inc.; 1961: 75-79.

Jorgensen, Jens E.; Carson, Ward W.; Chalupnik, James O.; Garbini, Joseph L. Skyline anchor dynamics test. Tech. Rep. FE-UW-7702. Seattle, WA: University of Washington, Mechanical Engineering; 1977.

Reutebuch, Stephen E. A computer model to predict the static guyline tensions in cable logging tower systems. Seattle, WA: University of Washington; 1978. Thesis.

## Appendix A
### List of Variables

| Variable | Description |
|---|---|
| A1 | Intermediate, used in catenary routine to find guyline lengths |
| A(1, 1) | Summation of x-components of loads and tensions |
| A(1, 2) | Summation of y-components of loads and tensions |
| A(2, 1) | Summation of x-components of variable tensions |
| A(2, 2) | Summation of y-components of variable tensions |
| A(3, 1) | Intermediate sum of x-components of loads and tensions |
| A(3, 2) | Intermediate sum of y-components of loads and tensions |
| A(4, 1) | Intermediate sum of x-components of loads and tensions |
| A(4, 2) | Intermediate sum of y-components of loads and tensions |
| A(5, 1) | Summation of z-components of loads and tensions |
| A(5, 2) | Summation of magnitudes of all tensions |

The A matrix is used for a variety of functions in the yarding segment of the program.

| | |
|---|---|
| A$ | String variable in plot routine |
| B(I, 1) | Azimuth from tower base to ith anchor |
| B(I, 2) | Horizontal distance from tower base to ith anchor |
| B(I, 3) | Elevation of ith anchor |
| B$ | String variable in plot routine |
| C | Tower compression |
| C1 | x-component of tower compression |
| C2 | z-component of tower compression |
| C3 | z-component of tower compression |
| C4 | z-component of tower base location vector |
| D | Horizontal distance from a guyline anchor to tower top |
| D0 | Tower top displacement in x-y plane |
| D1 | Tower top displacement in x-direction |
| D2 | Tower top displacement in y-direction |
| D3 | Tower top displacement in z-direction |
| D(1) | Previous D1 value used to compute tower system spring rates for a displacement in the x-direction |
| D(2) | Previous D2 value used to compute tower system spring rates for a displacement in the y-direction |
| D(3) | Intermediate to store D1 |
| D(4) | Intermediate to store D2 |
| D(5) | Initial x-component of tower top displacement |
| D(6) | Initial y-component of tower top displacement |
| E | Elevation of tower base |
| F | Error term in catenary tension iteration:<br>$\lvert \text{known unstretched length-computed unstretched length} \rvert$ |
| F0 | Magnitude of line load resultant |
| F1 | Summation of x-components of line loads |
| F2 | Summation of y-components of line loads |
| F3 | Magnitude of z-components of line loads |
| F(1) | x-component of ith operating line load |
| F(2) | y-component of ith operating line load |
| F(3) | z-component of ith operating line load |
| F8 | Previous value of error term |
| F9 | Numerical value of the derivative of the error term |
| G | Constant to convert degrees to radians |
| H | Tower height: from pivot to top |

| Variable | Description |
|---|---|
| I | Counter, flag |
| I9 | Counter |
| J | Counter, flag |
| K | Counter |
| K1 | Counter |
| K2 | Flag |
| K3 | Tolerance in final force balance |
| K(I, 1) | Diameter of ith guyline |
| K(I, 2) | Stretch coefficient of ith guyline |
| L(1) | Change in x-component of tower top displacement |
| L(2) | Change in y-component of tower top displacement |
| L(3) | Previous trial x-component of displacement |
| L(4) | Previous trial y-component of displacement |
| L$ | String variable in plot routine |
| M | Catenary parameter |
| M(I, 1) | Initial x-component of ith anchor location vector |
| M(I, 2) | Initial y-component of ith anchor location vector |
| M(I, 3) | Initial z-component of ith anchor location vector |
| M(I, 4) | Final x-component of ith anchor location vector |
| M(I, 5) | Final y-component of ith anchor location vector |
| M(I, 6) | Final z-component of ith anchor location vector |
| N | Number of guylines |
| N1 | Number of possible anchor locations |
| N(I, 1) | Initial x-direction cosine for ith guyline |
| N(I, 2) | Initial y-direction cosine for ith guyline |
| N(I, 3) | Initial z-direction cosine for ith guyline |
| Q | Distance from guyline drums to tower top |
| R | Distance from tower base to operating line drum |
| R1 | Resultant of guyline weight |
| S | Stretched guyline length |
| S0 | Unstretched guyline length |
| S(I, 1) | Initial chord length of ith guyline |
| S(I, 2) | Final chord length of ith guyline |
| S(I, 3) | Initial stretched length of ith guyline |
| S(I, 4) | Initial unstretched length of ith guyline |
| S(I, 5) | Final stretched length of ith guyline |
| T | Guyline tension |
| T1 | Computed guyline tension |
| T(I, 1) | x-component of ith guyline tension |
| T(I, 2) | y-component of ith guyline tension |
| T(I, 3) | z-component of ith guyline tension |
| T(I, 4) | ith guyline pretension |
| T(I, 5) | First trial pretension for ith guyline (later final tension for ith guyline) |
| T$(I, I) | ith element of string variable indicating whether the ith guyline pretension is fixed or variable |

| Variable | Description |
|---|---|
| U | Angle of resultant of operating line loads |
| V | Azimuth of resultant of operating line loads |
| V(1) | Change in unbalanced force in x-direction |
| V(2) | Change in unbalanced force in y-direction |
| W | Guyline weight per foot |
| X | Intermediate |
| X1 | System spring rate for change in the y-summation of guyline tensions and tower compression caused by a change in the displacement in the x-direction |
| X2 | System spring rate for change in the x-summation of guyline tensions and tower compression caused by a change in the displacement in the x-direction |
| X$ | String variable flag |
| Y | Intermediate variable |
| Y1 | System spring rate for change in the x-summation of guyline tensions and tower compression caused by change in displacement in the y-direction |
| Y2 | System spring rate for change in the x-summation of guyline tensions and tower compression caused by change in displacement in the y-direction |
| Y$ | String variable flag |
| Z$ | String variable flag |

# Appendix B

## Guyline Analysis Program Listing; HP 9845 Version

```
10   OPTION BASE 1
20   REM THIS PROGRAM PERFORMS A STRUCTURAL ANALYSIS OF THE VERTICAL
30   REM CABLE LOGGING TOWER SYSTEM.  GUYLINE TENSIONS ARE PREDICTED
40   REM FOR THE PARTICULAR TOWER SETUP AND OPERATING LINE
50   REM CONFIGURATION SPECIFIED BY THE USER.
60   REM FOR SPECIFIC DETAILS CONCERNING THE PROGRAM, REFER TO:
70   REM REUTEBUCH, STEPHEN E.  "A COMPUTER MODEL TO PREDICT STATIC
80   REM      GUYLINE TENSIONS IN CABLE LOGGING TOWER SYSTEMS," MS THESIS,
90   REM      UNIVERSITY OF WASHINGTON, SEATTLE, WA. 1978.
100  REM UP-DATED 5/2/78
110  REM CONVERTED TO HP 9845 BY S.E. REUTEBUCH 11/28/78
120  REM ***PROGRAM TO CALCULATE GUYLINE TENSION***
130  PRINTER IS 0
140  PRINT LIN(3);"          **GUYLINE TENSION AND DEFLECTION PROGRAM**";LIN(2)
150  DIM A(5,2),B(12,3),D(7),F(3),K(8,2),M(8,6),N(8,3),S(8,5),T(8,5)
160  DIM N$[10],T$[25],X$[2],Y$[40],Z$[2]
170  PRINTER IS 16
180  PRINT PAGE;LIN(3);"INSERT TOWER SETTING DATA TAPE IN THE LEFT TAPE DRIVE"
190  PRINT LIN(1);"PRESS CONT WHEN READY"
200  PAUSE
210  PRINT PAGE
220  PRINTER IS 0
230  G=PI/180
240  INPUT "NEW SETTING  (Y/N) ?",X1$
250  IF X1$="Y" THEN 500
260  INPUT "FILE NAME  (UP TO 6 CHARACTERS) ? ',N$[1,6]
270  N$[7,10]=":T14"
280  ON ERROR GOTO 310
290  ASSIGN N$ TO #1
300  GOTO 370
310  BEEP
320  BEEP
330  BEEP
340  DISP "!!!";N$[1,6];" DOES NOT EXIST ON THIS TAPE!!!"
350  WAIT 2500
360  GOTO 260
370  OFF ERROR
380  READ #1;B(*),E,N1,Y$
390  PRINT TAB(15),"PREVIOUSLY STORED SETTING--";Y$
400  PRINT
410  PRINT TAB(10);"NUMBER OF POSSIBLE ANCHOR LOCATIONS=";N1
420  PRINT TAB(10);"ELEVATION AT BASE OF TOWER=";E
430  PRINT TAB(17);"*POSSIBLE ANCHOR LOCATIONS*"
440  PRINT TAB(10);"NUMBER    AZIMUTH    DISTANCE    ELEVATION"
450  FOR I=1 TO N1
460  PRINT USING 470;I,B(I,1),B(I,2),B(I,3)
470  IMAGE M13D ,M10D ,M9D.1D ,M10D.1D
480  NEXT I
490  GOTO 530
500  DISP "SETTING NAME";
```

```
510  LINPUT Y$
520  PRINT TAB(100),"SETTING--";Y$
530  PRINT
540  DISP "TOWER HEIGHT";
550  INPUT H
560  PRINT TAB(10);"TOWER HEIGHT=";H;"FEET."
570  DISP "DISTANCE FROM THE GUYLINE DRUMS TO THE TOWER TOP";
580  INPUT Q
590  PRINT TAB(10);"DIST:  GUYLINE DRUMS TO TOWER TOP ";Q;" FEET."
600  IF X1$="N" THEN 740
610  DISP "ELEVATION AT TOWER BASE";
620  INPUT E
630  PRINT TAB(10);"ELEVATION AT TOWER BASE=";E;"FEET."
640  DISP "NUMBER OF POSSIBLE ANCHORS  (UP TO 12) ";
650  INPUT N1
660  PRINT TAB(10);"NUMBER OF POSSIBLE ANCHORS=";N1
670  PRINT TAB(17);"*POSSIBLE ANCHOR LOCATIONS*"
680  PRINT TAB(10);"NUMBER    AZIMUTH    DISTANCE    ELEVATION"
690  FOR I=1 TO N1
700  DISP "AZIMUTH,HORIZONTAL DISTANCE,ELEVATION FOR ANCHOR ";I;
710  INPUT B(I,1),B(I,2),3(I,3)
720  PRINT USING 470;I,B(I,1),B(I,2),B(I,3)
730  NEXT I
740  N=X=I=1
750  DISP "PLOT OF ALL POSS. ANCHORS (Y/N)";
760  LINPUT Z$
770  GOTO 1430
780  PRINT
790  IF X1$="N" THEN 990
800  X1$="N"
810  DISP "DO YOU WANT TO STORE SETTING";
820  LINPUT Z$
830  IF Z$="N" THEN 990
840  INPUT "FILE NAME (UP TO 6 CHARACTERS) ? ",N$[1,6]
850  N$[7,10]=":T14"
860  ON ERROR GOTO 900
870  CREATE N$,2
880  ASSIGN N$ TO #1
890  GOTO 960
900  BEEP
910  BEEP
920  BEEP
930  DISP "!!! ";N$;" IS AN IMPROPER OR DUPLICATE FILE NAME!!!"
940  WAIT 2500
950  GOTO 840
960  OFF ERROR
970  PRINT #1;B(*),E,N1,Y$
980  PRINT " STORED ON FILE ";N$[1,6]
990  PRINT
1000 PRINT "GUYLINE      *SELECTED ANCHOR LOCATIONS*          *GUYLINE*"
```

```
1010 PRINT " NUMBER    AZIMUTH   DISTANCE   ELEVATION      DIAMETER   ANGLE"
1020 N=1
1030 DISP "INITIAL TOWER LEAN: ANGLE,AZ";
1040 INPUT X,Y
1050 D0=H*SIN(X*G)
1060 D1=D0*COS(Y*G)
1070 D2=-D0*SIN(Y*G)
1080 D3=SQR(H^2-D1^2-D2^2)-H
1090 D(5)=D1
1100 D(6)=D2
1110 D(7)=D3
1120 DISP "SAME DIAMETER FOR ALL GUYLINES(Y/N)";
1130 LINPUT X$
1140 IF X$="N" THEN 1170
1150 DISP "DIAMETER OF GUYLINES";
1160 INPUT X
1170 DISP "SELECT UP TO 8 ANCHORS"
1180 WAIT 2500
1190 FIXED 0
1200 DISP "GUYLINE #";N;"= ANCHOR #";
1210 INPUT I
1220 IF I=0 THEN 1440
1230 IF X$="Y" THEN 1270
1240 DISP "DIAMETER FOR GUYLINE";N;
1250 INPUT K(N,1)
1260 GOTO 1280
1270 K(N,1)=X
1280 M(N,1)=B(I,2)*COS(B(I,1)*G)-D1
1290 M(N,2)=--B(I,2)*SIN(B(I,1)*G)-D2
1300 M(N,3)=B(I,3)-E-H--D3
1310 S(N,1)=SQR(M(N,1)^2+M(N,2)^2+M(N,3)^2)
1320 N(N,1)=M(N,1)/S(N,1)
1330 N(N,2)=M(N,2)/S(N,1)
1340 N(N,3)=M(N,3)/S(N,1)
1350 K(N,2)=K(N,1)^2*6.504E6/(S(N,1)+0)
1360 PRINT USING 1370;N,B(I,1),B(I,2),B(I,3),K(N,1)
1370 IMAGE #,M3D ,M11D ,2(M9D.1D ),M9D.3D
1380 PRINT USING 1390;ATN(ABS(M(N,3)/SQR(M(N,1)^2+M(N,2)^2)))/G
1390 IMAGE M7D
1400 N=N+1
1410 IF N=9 THEN 1440
1420 IF N>N1 THEN 1440
1430 GOTO 1200
1440 N=N-1
1450 INPUT "GUYLINE CABLE FACTOR OF SAFETY ? ",Safety_factor
1460 PRINT USING "38A,3D";"      GUYLINE CABLE FACTOR OF SAFETY IS',Safety_factor
1470 GOTO 1960
1480 REM *** PLOT ROUTINE ***
1490 IF Z$="N" THEN 1530
1500 PLOTTER IS 13,"GRAPHICS"
```

```
1510 GRAPHICS
1520 LOCATE 15,85,10,80
1530 B1=0
1540 FOR I=1 TO N1
1550 IF B(I,2)<B1 THEN 1570
1560 B1=B(I,2)
1570 NEXT I
1580 IF Z$="N" THEN 780
1590 SHOW -B1,B1,-B1,B1
1600 GOTO 1660
1610 LINE TYPE 3
1620 MOVE -B1-.1*B1,0
1630 DRAW B1+.1*B1,0
1640 MOVE 0,-B1-.1*B1
1650 DRAW 0,B1+.1*B1
1660 LINE TYPE 1
1670 LDIR 0
1680 MOVE 0,0
1690 LORG 5
1700 LABEL USING "A";"*"
1710 LORG 1
1720 CSIZE 3
1730 FOR I=1 TO N1
1740 MOVE 0,0
1750 DRAW B(I,2)*SIN(B(I,1)*G),B(I,2)*COS(B(I,1)*G)
1760 LABEL USING "2D";I
1770 NEXT I
1780 SETGU
1790 CSIZE 5
1800 MOVE 5,90
1810 LABEL USING "9A,40A";"SETTING--",Y$
1820 CSIZE 3,.5
1830 LABEL USING "30A";"ALL POSSIBLE ANCHORS"
1840 MOVE 75,80
1850 LORG 5
1860 LABEL USING "4A";"AZ=0"
1870 MOVE 82,77
1880 DRAW 82,87
1890 DRAW 83,85
1900 DRAW 81,85
1910 DRAW 82,87
1920 WAIT 8000
1930 DUMP GRAPHICS
1940 EXIT GRAPHICS
1950 GOTO 780
1960 Z$="A"
1970 DISP "SAME PRETENSION FOR ALL GUYLINES  (Y/N)";
1980 LINPUT X$
1990 IF X$="Y" THEN 2100
2000 FOR I=1 TO N
```

```
2010 DISP "DESIRED PRETENSION IN GUYLINE ";I;"F.V";
2020 INPUT T(I,4),T$[I,I]
2030 IF T(I,4)>=S(I,1)+K(I,1)^2+1.85*3 THEN 2070
2040 DISP "TENSION IN GUYLINE";I;"MUST BE";S(I,1)+K(I,1)^2+1.85*3
2050 WAIT 3000
2060 GOTO 2010
2070 T(I,5)=T(I,4)
2080 NEXT I
2090 GOTO 2230
2100 DISP "DESIRED PRETENSION IN GUYLINES";
2110 INPUT T0
2120 J=0
2130 FOR I=1 TO N
2140 IF T0>=S(I,1)+K(I,1)^2*1.85*3 THEN 2180
2150 J=1
2160 DISP "TENSION IN GUYLINE ";I;"MUST BE";S(I,1)+K(I,1)^2+1.85*3
2170 WAIT 4000
2180 T(I,4)=T0
2190 T$[I,I]="V"
2200 T(I,5)=T(I,4)
2210 NEXT I
2220 IF J<>0 THEN 2100
2230 PRINT
2240 PRINT CHR$(130)
2250 PRINT TAB(10);"** INITIAL OPERATING LINE AND GUYLINE TENSIONS **"
2260 PRINT CHR$(128)
2270 DISP "AZIMUTH FROM TOWER BASE TO OPERATING LINE DRUMS";
2280 INPUT R
2290 PRINT LIN(1);"AZIMUTH: TOWER BASE TO OPER. LINE DRUMS= ";R;" DEGREES"
2300 PRINT
2310 F1=0
2320 F2=0
2330 F3=0
2340 I=1
2350 PRINT "OPERATING LINES                              TENSION      ANGLE  AZIMUTH   DRUM DIST
"
2360 DISP "TENSION IN THE OPERATING LINE AT TOWER TOP (LB)";
2370 INPUT F0
2380 IF F0=0 THEN 2600
2390 DISP "OPERATING LINE ANGLE FROM THE HORIZONTAL (DEG.)";
2400 INPUT U
2410 DISP "AZIMUTH OF OPERATING LINE LEAD (DEG.)";
2420 INPUT V
2430 DISP "DISTANCE FROM TOWER BASE TO OPERATING LINE DRUM";I;
2440 INPUT R1
2450 PRINT "     OPER. LINE";I;
2460 PRINT USING "20D,3(9D)";F0,U,V,R1
2470 I=I+1
2480 F(1)=R1*COS(R*G)
2490 F(2)=-R1*SIN(R*G)
2500 F(3)=-H
```

```
2510 X=SQR((F(1)-D1)^2+(F(2)-D2)^2+(F(3)-D3)^2)
2520 F(1)=(F(1)-D1)/X
2530 F(2)=(F(2)-D2)/X
2540 F(3)=(F(3)-D3)/X
2550 X=F0*COS(U*G)
2560 F1=F1+X*COS(V*G)+F0*F(1)
2570 F2=F2-X*SIN(V*G)+F0*F(2)
2580 F3=F3-F0*SIN(U*G)+F0*F(3)
2590 GOTO 2360
2600 F0=SQR(F1^2+F2^2+F3^2)
2610 U=-ATN(F3/(SQR(F1^2+F2^2)+1E-50))/G
2620 V=0
2630 IF F2<>0 THEN 2670
2640 IF F1>=0 THEN 2700
2650 V=180
2660 GOTO 2700
2670 V=90+ATN(F1/F2)/G
2680 IF F2<0 THEN 2700
2690 V=V+180
2700 IF Z$="B" THEN 2730
2710 F4=F1
2720 F5=F2
2730 PRINT "OPER. LINES VECTOR RESULTANT";
2740 PRINT USING 2750;F0,U,V
2750 IMAGE 9D ,2(9D )
2760 IF Z$="B" THEN 4080
2770 A(1,1)=0
2780 A(1,2)=0
2790 A(2,1)=0
2800 A(2,2)=0
2810 A(5,1)=0
2820 A(5,2)=0
2830 FOR I=1 TO N
2840 T(I,1)=T(I,4)*N(I,1)
2850 T(I,2)=T(I,4)*N(I,2)
2860 T(I,3)=T(I,4)*N(I,3)
2870 A(1,1)=A(1,1)+T(I,1)
2880 A(1,2)=A(1,2)+T(I,2)
2890 A(5,1)=A(5,1)+T(I,3)
2900 A(5,2)=A(5,2)+T(I,4)
2910 IF T$[I,I]="F" THEN 2940
2920 A(2,1)=A(2,1)+ABS(T(I,1))
2930 A(2,2)=A(2,2)+ABS(T(I,2))
2940 NEXT I
2950 I9=0
2960 GOTO 4910
2970 IF ABS(F4+A(1,1))<100 THEN 3010
2980 J=1
2990 K=2
3000 GOTO 3040
```

```
3010 IF ABS(F5+A(1,2))<100 THEN 3410
3020 J=2
3030 K=1
3040 A(3,1)=A(1,1)+F1
3050 A(3,2)=A(1,2)+F2
3060 A(4,1)=A(2,1)
3070 A(4,2)=A(2,2)
3080 A(1,1)=A(1,2)=A(2,1)=A(2,2)=A(5,1)=A(5,2)=0
3090 FOR I=1 TO N
3100 IF T$[I,I]="F" THEN 3250
3110 IF ABS(T(I,J))<.1 THEN 3250
3120 R=ABS((T(I,J)-ABS(T(I,J))/A(4,J)*A(3,J))/T(I,J))
3130 T(I,J)=T(I,J)*R
3140 T(I,K)=T(I,K)*R
3150 T(I,3)=T(I,3)*R
3160 T(I,4)=SQR(T(I,1)^2+T(I,2)^2+T(I,3)^2)
3170 IF T(I,4)>=S(I,1)*K(I,1)^2*1.85*2 THEN 3250
3180 IF X>20 THEN 3380
3190 X=X+1
3200 T(I,4)=20*S(I,1)*K(I,1)^2*1.85
3210 T(I,1)=T(I,4)*N(I,1)
3220 T(I,2)=T(I,4)*N(I,2)
3230 T(I,3)=T(I,4)*N(I,3)
3240 GOTO 3100
3250 A(1,1)=A(1,1)+T(I,1)
3260 A(1,2)=A(1,2)+T(I,2)
3270 A(5,1)=A(5,1)+T(I,3)
3280 A(5,2)=A(5,2)+T(I,4)
3290 IF T$[I,I]="F" THEN 3320
3300 A(2,1)=A(2,1)+ABS(T(I,1))
3310 A(2,2)=A(2,2)+ABS(T(I,2))
3320 X=0
3330 NEXT I
3340 I9=I9+1
3350 DISP "ITERATION # ";I9
3360 IF I9>25 THEN 3380
3370 GOTO 4910
3380 PRINT "!!!!!!PRETENSION CONVERGENCY PROBLEM!!!!!!"
3390 PRINT "TRY A NEW PRETENSION ARRANGEMENT"
3400 GOTO 1970
3410 REM ****INITIAL UNSTRETCHED CATENARY LENGTH******
3420 DEF FNS(X)=X+X^3/6+X^5/120
3430 DEF FNC(X)=1+X^2/2+X^4/24+X^6/720
3440 DEF FNA(X)=1/X+X/3-X^3/45+2*X^5/945
3450 FOR I=1 TO N
3460 T=T(I,4)
3470 D=SQR(M(I,1)^2+M(I,2)^2)
3480 Y=-M(I,3)
3490 W=K(I,1)^2*1.85
3500 R1=W*S(I,1)
```

```
3510 X=D/2
3520 J=0
3530 K=1
3540 A1=SQR((R1*Y*X/D^2)^2-(1+(Y/D)^2)*(R1^2*(X/D)^2-T^2))
3550 M=(-R1*Y*X/D^2+A1)/(1+(Y/D)^2)/W
3560 D0=D/2/M
3570 S=SQR(Y^2+(2*M*FNS(D0))^2)
3580 R1=W*S
3590 X=D/2-Y/S*(M-D/2*FNA(D0))
3600 T1=W/2*(S*FNA(D0)+Y)
3610 IF ABS(T1-T)<T/10000 THEN 3680
3620 IF K>20 THEN 3650
3630 K=K+1
3640 GOTO 3540
3650 PRINT "!!!!!PRETENSION IN GUYLINE ";I;"TOO LOW!!!!!!"
3660 PRINT "TRY A NEW PRETENSION ARRANGEMENT"
3670 J=1
3680 S(I,3)=S
3690 S(I,4)=S-(T-W*Y/2)/K(I,2)
3700 S(I,5)=S
3710 NEXT I
3720 IF J<>0 THEN 1970
3730 PRINT
3740 PRINT "GUYLINE             *PRETENSIONS*                 *INITIAL LENGTHS*"
3750 PRINT "NUMBER          INPUT        BALANCED       STRETCHED    UNSTRETCHED"
3760 FOR I=1 TO N
3770 PRINT USING 3780;I,T(I,5),T(I,4),S(I,3),S(I,4)
3780 IMAGE M3D ,M14D ,M12D ,M12D.2D ,M10D.2D
3790 NEXT I
3800 FIXED 3
3810 IF (D1>0) AND (D2<=0) THEN X=-ATN(D2/D1)/G
3820 IF D1<0 THEN X=180-ATN(D2/D1)/G
3830 IF (D1>0) AND (D2>=0) THEN X=360-ATN(D2/D1)/G
3840 IF (D1=0) AND (D2=0) THEN X=0
3850 IF (D1=0) AND (D2>0) THEN X=270
3860 IF (D1=0) AND (D2<0) THEN X=90
3870 IF INT(X)=360 THEN X=0
3880 PRINT USING "45A,2D.2D,7D";"INITIAL TOWER TOP DEFLECTION: DIST, AZ   ";SQ(
D1^2+D2^2+D3^3),X
3890 FIXED 0
3900 PRINT "INITIAL TOWER COMPRESSION   ";SQR(C1^2+C2^2+C3^2);" POUNDS"
3910 DISP "ARE PRETENSIONS SATISFACTORY";
3920 LINPUT X$
3930 IF X$="N" THEN 1960
3940 DISP "SETUP NUMBER";
3950 INPUT A9
3960 DISP "DO YOU WANT A PLOT";
3970 LINPUT X$
3980 IF X$<>"Y" THEN 4000
3990 GOSUB 6750
4000 REM *** Z$="B" INDICATES FINAL LOADS SECTION OF PROGRAM****
```

```
4010 DISP "RUN NAME OR NUMBER (UP TO 25 CHARACTERS) ";
4020 LINPUT T$[1,25]
4030 Z$="B"
4040 PRINT CHR$(132);"   FINAL OPERATING LINE TENSIONS FOR SETUP $";
4050 PRINT USING "3D,2X,5A,25A";A9,"RUN--",T$
4060 PRINT CHR$(128)
4070 GOTO 2270
4080 K1=0
4090 ON ERROR GOTO 4330
4100 L3=D(5)
4110 L4=D(6)
4120 K3=2000
4130 MAT A=(0)
4140 D1=(F1-F4)/(K(1,2)*N/3)+D(5)
4150 IF ABS(F1)>1000 THEN 4170
4160 D1=D(5)+.49
4170 D2=D(6)
4180 GOTO 4280
4190 X1=(A(1,2)+F5)/(D1-D(5))
4200 X2=(A(1,1)+F4)/(D1-D(5))
4210 D(1)=D(5)
4220 A(3,1)=-F4
4230 A(3,2)=-F5
4240 D1=D(5)
4250 D2=(F2-F5)/(K(1,2)*N/3)+D(6)
4260 IF ABS(F2)>1000 THEN 4280
4270 D2=D(6)+.49
4280 REM ********SOLUTION FOR FINAL CATENARY TENSION******
4290 DEF FNB(X)=4/3*M*A1*A3
4300 DEF FND(X)=4/3*M*A2*A3
4310 DEF FNE(X)=-X^3/3-X^5/30
4320 IF H^2-D1^2-D2^2>0 THEN 4370
4330 PRINT "!!!!!!!YOUR TOWER JUST WENT DOWN THE HILL!!!!!"
4340 PRINT "LOAD WAS TOO LARGE OR SYSTEM IS UNSTABLE"
4350 OFF ERROR
4360 GOTO 6250
4370 D3=SQR(H^2-D1^2-D2^2)-H
4380 FOR I=1 TO N
4390 F=0
4400 S0=S(I,4)
4410 M(I,4)=M(I,1)-(D1-D(5))
4420 M(I,5)=M(I,2)-(D2-D(6))
4430 M(I,6)=M(I,3)-(D3-D(7))
4440 D=SQR(M(I,4)^2+M(I,5)^2)
4450 Y=-M(I,6)
4460 S(I,2)=SQR(D^2+Y^2)
4470 W=K(I,1)^2*1.85
4480 K=K(I,2)
4490 J=1
4500 IF K1>0 THEN 4530
```

```
4510 S=S(I,3)
4520 GOTO 4540
4530 S=S(I,5)
4540 X=W*S/(2*K*(S-S0))
4550 X=LOG((1+X)/ABS(1-X))
4560 M=D/X
4570 D0=D/2/M
4580 A1=FNS(D0)
4590 A2=FNC(D0)
4600 A3=FNE(D0)
4610 A4=A2/A1
4620 S=SQR(Y^2+(2*M*A1)^2)
4630 F8=F
4640 F=S0-S+W/2/K*S*A4
4650 IF J=1 THEN 4670
4660 IF ABS(F)<.0001 THEN 4780
4670 F9=-FNB(D0)+W/2/K*(S*(1/A1)^2*D^2/M^2+FND(D0))
4680 X=M-F/F9
4690 IF X>.01 THEN 4720
4700 F9=F9*2
4710 GOTO 4680
4720 M=X
4730 IF ABS(F)>.001 THEN 4750
4740 IF ABS(ABS(F)-ABS(F8))<.0001 THEN 4780
4750 IF J=40 THEN 4780
4760 J=J+1
4770 GOTO 4570
4780 T(I,5)=W/2*(S*A4+Y)
4790 S(I,5)=S
4800 NEXT I
4810 A(1,1)=0
4820 A(1,2)=0
4830 A(5,1)=0
4840 A(5,2)=0
4850 FOR I=1 TO N
4860 A(1,1)=A(1,1)+T(I,5)*M(I,4)/S(I,2)
4870 A(1,2)=A(1,2)+T(I,5)*M(I,5)/S(I,2)
4880 A(5,1)=A(5,1)+T(I,5)*M(I,6)/S(I,2)
4890 A(5,2)=A(5,2)+T(I,5)
4900 NEXT I
4910 IF Q>0 THEN 4930
4920 A(5,2)=0
4930 REM *****COMPUTE THE COMPRESSION IN THE TOWER*****
4940 C4=H+D3
4950 C3=A(5,2)*C4/H-A(5,1)-F3
4960 IF Z$="A" THEN 4990
4970 IF K1>1 THEN 4990
4980 C3=A(5,2)*C4/H-A(5,1)
4990 C1=C3*D1/C4
5000 C2=C3*D2/C4
```

```
5010 C=SQR(C1^2+C2^2+C3^2)
5020 A(1,1)=A(1,1)+C1-A(5,2)*D1/H
5030 A(1,2)=A(1,2)+C2-A(5,2)*D2/H
5040 IF Z$="A" THEN 2970
5050 K1=K1+1
5060 IF K1>25 THEN 4330
5070 DISP "ITERATION # ";K1
5080 IF X$="A" THEN 6520
5090 IF X$="B" THEN 6670
5100 IF K1=1 THEN 4190
5110 IF K1>2 THEN 5310
5120 Y1=(A(1,1)+F4)/(D2-D(6))
5130 Y2=(A(1,2)+F5)/(D2-D(6))
5140 D(2)=D(6)
5150 IF ABS(F1-F4)>ABS(F2-F5) THEN 5250
5160 A(3,1)=-F4
5170 A(3,2)=-F5
5180 K2=1
5190 D1=D(5)
5200 D2=-(F2-F5)/Y2+D(6)
5210 IF ABS(D2-D(2))<.5 THEN 4320
5220 GOSUB 6620
5230 D2=D2+SGN(D2)*.5
5240 GOTO 5310
5250 K2=2
5260 D2=D(6)
5270 D1=-(F1-F4)/X2+D(5)
5280 IF ABS(D1-D(1))<.5 THEN 4320
5290 GOSUB 6470
5300 D1=D1+SGN(D1)*.5
5310 REM ******CHECK FORCE BALANCE IN X-Y DIRECTIONS******
5320 IF K2=2 THEN 5570
5330 IF ABS(F1+A(1,1))<K3 THEN 5570
5340 L3=D1
5350 L4=D2
5360 K2=2
5370 L1=-(F1+A(1,1))/X2
5380 A(4,1)=A(4,1)+1
5390 IF A(4,1)<5 THEN 5410
5400 GOSUB 6410
5410 D1=D1+L1
5420 IF ABS(D1)<ABS(D(1))+.5 THEN 5440
5430 GOSUB 6410
5440 V2=L1*X1
5450 L2=-V2/Y2
5460 D2=D2+L2
5470 K2=1
5480 IF ABS(D2)<ABS(D(2))+.5 THEN 5500
5490 GOSUB 6410
5500 K2=2
```

```
5510 V1=L2*Y1
5520 L1=-V1/X2
5530 D1=D1+L1
5540 IF ABS(D1)<ABS(D(1))+.5 THEN 5560
5550 GOSUB 6410
5560 GOTO 4320
5570 IF ABS(F2+A(1,2))<K3 THEN 5810
5580 L3=D1
5590 L4=D2
5600 K2=1
5610 L2=-(F2+A(1,2))/Y2
5620 A(4,2)=A(4,2)+1
5630 IF A(4,2)<5 THEN 5650
5640 GOSUB 6410
5650 D2=D2+L2
5660 IF ABS(D2)<ABS(D(2))+.5 THEN 5680
5670 GOSUB 6410
5680 V1=L2*Y1
5690 L1=-V1/X2
5700 D1=D1+L1
5710 K2=2
5720 IF ABS(D1)<ABS(D(1))+.5 THEN 5740
5730 GOSUB 6410
5740 K2=1
5750 V2=L1*X1
5760 L2=-V2/Y2
5770 D2=D2+L2
5780 IF ABS(D2)<ABS(D(2))+.5 THEN 5800
5790 GOSUB 6410
5800 GOTO 4320
5810 IF ABS(F1+A(1,1))>K3 THEN 5340
5820 K3=500
5830 IF ABS(F1+A(1,1))>500 THEN 5340
5840 IF ABS(F2+A(1,2))>500 THEN 5580
5850 PRINT
5860 PRINT "GUYLINE      *STRETCHED LENGTHS*           *GUYLINE TENSIONS*"
5870 PRINT " NUMBER   INITIAL    FINAL    CHANGE    INITIAL    FINAL    CHANGE
5880 OFF ERROR
5890 J=0
5900 Elastic_flag=0
5910 FOR I=1 TO N
5920 IF T(I,5)>100000*K(I,1)^2/Safety_factor THEN 5960
5930 PRINT USING 5940;I,S(I,3),S(I,5),S(I,5)-S(I,3),T(I,4),T(I,5),T(I,5)-T(I,4
5940 IMAGE M3D ,M9D.2D ,M5D.2D ,M6D.2D ,M9D ,M8D ,M9D
5950 GOTO 6000
5960 PRINT USING 5970;I,S(I,3),S(I,5),S(I,5)-S(I,3),T(I,4),T(I,5),T(I,5)-T(I,4
5970 IMAGE M3D ,M9D.2D ,M5D.2D ,M6D.2D ,M9D ,M8D ,"!!!",M6D
5980 J=1
5990 IF T(I,5)>100000*K(I,1)^2*.6 THEN Elastic_flag=1
6000 NEXT I
```

```
6010 IF J=0 THEN 6050
6020 PRINT USING "55A,3D";"!!!-GUYLINE WORKING LOAD EXCEEDED WITH SAFETY FACTOR
OF",Safety_factor
6030 IF Elastic_flag=0 THEN 6050
6040 PRINT USING "80A";"ELASTIC LIMIT OF CABLE EXCEEDED--THIS LOADING IS BEYOND
THE RANGE OF THE MODEL"
6050 PRINT
6060 FIXED 0
6070 PRINT "UNBALANCED X-FORCE=";F1+A(1,1);"    UNBALANCED Y-FORCE=";F2+A(1,2)
6080 FIXED 3
6090 IF (D1>0) AND (D2<=0) THEN X=-ATN(D2/D1)/G
6100 IF D1<0 THEN X=180-ATN(D2/D1)/G
6110 IF (D1>0) AND (D2>=0) THEN X=360-ATN(D2/D1)/G
6120 IF (D1=0) AND (D2=0) THEN X=0
6130 IF (D1=0) AND (D2>0) THEN X=270
6140 IF (D1=0) AND (D2<0) THEN X=90
6150 IF INT(X)=360 THEN X=0
6160 PRINT USING "43A,2D.2D,7D";"FINAL TOWER DEFLECTION: DIST, AZ  ";SQR(D1^2+D2
^2+D3^2),X
6170 FIXED 0
6180 PRINT "FINAL TOWER COMPRESSION ";SQR(C1^2+C2^2+C3^2);" POUNDS"
6190 PRINT "NUMBER OF ITERATIONS=";K1
6200 PRINT TAB(100),TAB(100)
6210 DISP "DO YOU WANT A PLOT";
6220 LINPUT X$
6230 IF X$<>"Y" THEN 6250
6240 GOSUB 6750
6250 D1=D(5)
6260 D2=D(6)
6270 D3=D(7)
6280 D(1)=0
6290 D(2)=0
6300 D(3)=0
6310 D(4)=0
6320 X$="Y"
6330 PRINTER IS 16
6340 PRINT "1=NEW LOAD";TAB(30);"2=NEW PRETENSIONS"
6350 PRINT "3=NEW ANCHOR ARRANGEMENT";TAB(30);"4=STOP"
6360 INPUT "CHOOSE ONE OF THE ABOVE  (1-4) ? ",X
6370 PRINT PAGE
6380 PRINTER IS 0
6390 ON X GOTO 4000,1960,740,6400,7710
6400 STOP
6410 REM ***SUBROUTINE TO UPDATE SPRING RATES***
6420 A(3,1)=A(1,1)
6430 A(3,2)=A(1,2)
6440 IF K2=1 THEN 6600
6450 A(4,1)=0
6460 D1=D1+SGN(D1)*.5
6470 X$="A"
6480 D(1)=L3
6490 D(4)=D2
6500 D2=L4
```

```
6510 GOTO 4320
6520 D2=D(4)
6530 X$="Y"
6540 X1=(A(1,2)-A(3,2))/(D1-D(1))
6550 X2=(A(1,1)-A(3,1))/(D1-D(1))
6560 D(1)=D1
6570 L3=D1
6580 D1=D1-SGN(D1)*.5
6590 RETURN
6600 D2=D2+SGN(D2)*.5
6610 A(4,2)=0
6620 X$="B"
6630 D(2)=L4
6640 D(3)=D1
6650 D1=L3
6660 GOTO 4320
6670 D1=D(3)
6680 X$="Y"
6690 Y1=(A(1,1)-A(3,1))/(D2-D(2))
6700 Y2=(A(1,2)-A(3,2))/(D2-D(2))
6710 D(2)=D2
6720 L4=D2
6730 D2=D2-SGN(D2)*.5
6740 RETURN
6750 REM *** PLOT ROUTINE ***
6760 PLOTTER IS 13,"GRAPHICS"
6770 GRAPHICS
6780 LOCATE 15,85,10,80
6790 SHOW -B1,B1,-B1,B1
6800 GOTO 6860
6810 LINE TYPE 3
6820 MOVE -B1-.1*B1,0
6830 DRAW B1+.1*B1,0
6840 MOVE 0,-B1-.1*B1
6850 DRAW 0,B1+.1*B1
6860 LINE TYPE 1
6870 LDIR 0
6880 CSIZE 3
6890 LORG 5
6900 IF (D1=0) AND (D2=0) THEN 6930
6910 MOVE -D2,D1
6920 LABEL USING "A";"+"
6930 J=0
6940 LORG 1
6950 FOR I=1 TO N
6960 MOVE -D2,D1
6970 DRAW -M(I,2),M(I,1)
6980 LABEL USING "2D";J
6990 IF Z$="B" THEN 7020
7000 LABEL USING "6D";T(I,4)
```

```
7010 GOTO 7070
7020 IF T(I,5)>100000*F(I,1)/2/Safety_factor THEN 7050
7030 LABEL USING "6D";T(I,5)
7040 GOTO 7070
7050 LABEL USING "6D,4A";T(I,5),"(*)"
7060 J=1
7070 NEXT I
7080 IF F0=0 THEN 7160
7090 LINE TYPE 3
7100 MOVE -D2,D1
7110 DRAW B1/2*SIN(V+G),B1/2*COS(V+G)
7120 LINE TYPE 1
7130 LORG 5
7140 LABEL USING "A";"R"
7150 LORG 1
7160 SETGU
7170 IF J=0 THEN 7200
7180 MOVE 0,0
7190 LABEL USING "55A,3D";"(*)-GUYLINE WORKING LOAD EXCEEDED WITH SAFETY FACTOR
OF",Safety_factor
7200 MOVE 5,94
7210 CSIZE 5
7220 LABEL USING "9A,40A";"SETTING--",Y$
7230 CSIZE 3
7240 MOVE 5,89
7250 IF Z$="B" THEN 7300
7260 LABEL USING "13A,2D";"TRIAL SETUP #",A9
7270 MOVE 5,86
7280 LABEL USING "30A";"GUYLINE PRETENSIONS"
7290 GOTO 7330
7300 LABEL USING "13A,2D,4X,5A,25A";"TRIAL SETUP #",A9,"RUN--",T$
7310 MOVE 5,86
7320 LABEL USING "30A";"FINAL GUYLINE TENSIONS"
7330 IF F0=0 THEN 7380
7340 MOVE 5,83
7350 LABEL USING "30A";"LOAD RESULTANT (MAG,ANGLE,AZ)"
7360 MOVE 5,80
7370 LABEL USING "4X,3(6D)";F0,U,V
7380 LORG 5
7390 MOVE 75,80
7400 CSIZE 3
7410 LABEL USING "4A";"AZ=0"
7420 MOVE 82,77
7430 DRAW 82,87
7440 DRAW 83,85
7450 DRAW 81,85
7460 DRAW 82,87
7470 WAIT 8000
7480 DUMP GRAPHICS
7490 EXIT GRAPHICS
7500 PRINT LIN(2)
7510 RETURN
```

Carson, Ward W.; Jorgensen, Jens E.; Reutebuch, Stephen E.; Bramwell, William J.
A procedure for analysis of guyline tension. Gen. Tech. Rep. PNW-142. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 45 p.

Most cable logging operations use a spar held in place near the landing by a system of guylines and anchors. Safety and economic considerations require that overloads be avoided and that the spar remain stable. This paper presents a procedure and a computer program to estimate the guyline and anchor loads on a particular system configuration by a specific set of operating line tension loads. A brief description of the analytical model used for the computations is included. There are instructions on the use of the computer program, a description of the necessary outputs, and a program listing for those who wish to prepare the program for use on other computer facilities.

Keywords: Logging equipment engineering, cable skidding equipment, models, computer programs/programing.

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GPO 995-917

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**Forest Service**

Pacific Northwest
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# Programable Calculator Programs to Solve Softwood Volume and Value Equations

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Janet K. Ayer Sachet

**Author**

Janet K. Ayer Sachet is a forester at the Pacific Northwest Forest and Range Experiment Station, 809 N.E. 6th Ave., Portland, OR 97232.

## Abstract

Sachet, Janet K. Ayer. Programable calculator programs to solve softwood volume and value equations. Gen. Tech. Rep. PNW-143. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 12 p.

This paper presents product value and product volume equations as programs for handheld calculators. These tree equations are for inland Douglas-fir, young-growth Douglas-fir, western white pine, ponderosa pine, and western larch. Operating instructions and an example are included.

Keywords: Mathematical programing, calculators, volume estimation, timber value.

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## Introduction

This paper presents programs and operating instructions for programable calculators that will solve equations for estimating the product value and product volume for several species of western softwood sawtimber. The timber resource for which equations have been published are: inland Douglas-fir (Lane and others 1970), young-growth coast Douglas-fir (Fahey 1980), western white pine (Snellgrove and others 1973), old-growth ponderosa pine (Plank 1981), and western larch (Plank and others 1978).

The equations provide a method of determining the lumber selling value and product volume of trees from standing tree measurements. They are an improvement over conventional appraisals using discrete log grades. The entire tree bole does not need to be examined for individual log grades because only a few basic tree measurements are required. Also, the equations are capable of showing differences in quality that would conventionally be lumped within the same grade.

As originally published, the equations appear complex and difficult to use. This paper attempts to improve their usability with currently available and inexpensive technology. The prices used for developing the value equations are included, along with instructions for adjusting the values to those in the current marketplace.

## Description of the Programs

Two programs have been written for the Hewlett-Packard (HP) 97 and 67 [1] calculators: one for the volume equations and one for the value equations. The operating instructions (see page 2) are the same for both programs. A step-by-step example using the value equation is on page 3.

Information for each species is presented in three parts (see appendix 1). Part 1 gives the breakdown of products manufactured by grade, the 1978 average prices for these items, and the percent of the total lumber (or veneer) tally measured by grade in the study. The second part contains a description of the equations for the species — the variables and the coefficients, and a list of the HP storage registers for the coefficients. Part 3 lists the steps for using the program for the selected species.

## Value Adjustment

The six value equations, as originally published, have been updated using average 1978 prices and regression analysis to develop new coefficients. To adjust the value equations to current prices, two approaches can be taken. If the current $/MBF for each lumber (or veneer) grade retain the same relative standings as the 1978 prices (for example, if the price of Utility grade is twice the price for Economy grade), make a percent adjustment to the final tree value. For example, if current prices have increased 5 percent, multiply the tree value by 1.05. If the relative prices for the different grades change, however, develop new coefficients using regression analysis. The data for doing this are available from the Timber Quality Research Project, Pacific Northwest Forest and Range Experiment Station, 809 N.E. 6th Ave., Portland, OR 97232.

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[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

# User's Guide

## General Information

Some knowledge of Hewlett-Packard 97 and 67 calculator operation is presumed.

The value program and the volume program each contain six equations; only one equation can be solved at a time.

To store the program on a card, set the calculator switch to PRGM and key in all the steps for one program (appendix 2). To store the entire program, pass both sides of a blank card through the card reader. After the program is recorded on a card, set the calculator switch to RUN.

To store the coefficients on a card, set the calculator switch to RUN and store the coefficients for one species equation in the registers designated in appendix 1, part 2. Press f W/DATA and load one side of a blank card into the card reader. Coefficients for two equations can be stored on one card by using sides 1 and 2.

## Program Operation

| STEP | INSTRUCTIONS |
|---|---|
| 1 | Set the calculator switches to RUN (HP-97 and 67) and MAN (manual, HP-9 only). |
| 2 | Load side 1 and side 2 of either the value program card or the volume program card. |
| 3 | Clear storage registers (f CL REG). |
| 4 | Select the desired species equation and store the coefficients in the register specified in appendix 1, part 2 for that species. (If the coefficients are stored on a card, load the card.) |
| 5 | Press the key for the desired species equation:<br>A for inland Douglas-fir<br>B for young-growth coast Douglas-fir lumber<br>f b for young-growth coast Douglas-fir veneer<br>C for western white pine<br>D for ponderosa pine<br>E for western larch |
| 6 | Enter data items one at a time during calculator pauses; follow each entry with R/S key. (For order of entry, see appendix 1, part 3.) All variables fc an equation must be entered, enter a zero when a variable is undefined or zero. When a mistake is made while entering data, begin the program again by pressing the appropriate key, A to E, then re-enter all the variables. |
| 7 | For additional solutions to the same equation, go to step 5. |
| 8 | For solutions to a different species equation, go to step 3. |

## List of Variables and Symbols in the Equations

The following is a description of the variables used in the various equations (appendix 1, part 2). Each equation uses a different combination of the variables in this list.

| SYMBOL | EXPLANATION |
|---|---|
| A | Presence or absence of defect (1 = defect, 0 = none). |
| B | Diameter (in inches) of the largest limb in the butt 16-foot log. |
| C | Height to continuous live crown of two or more quadrants (in feet). |
| D | D.b.h. (in inches). |
| $F_{16}$ | Number of limb-free and defect-free faces in the butt 16-foot log. |
| $F_{32}$ | Number of limb-free and defect-free faces in the butt 32-foot log. |
| H | Total height of tree (in feet). |
| K | Largest knot in the butt 16-foot log (in inches). |
| L | Height to the first live limb (in feet). |
| P | Estimated percent defect of tree or of gross cruise volume. |
| S | Length of basal scar (in feet). |

## Example of Program Operation

Determine the lumber selling value of a young-growth Douglas-fir with these field measurements: D.b.h. = 24.5 inches, total height = 142 feet, height to crown = 75 feet, largest knot in the first log = 3 inches, basal scar = 0, and the estimated scaling defect percent = 10.

Load sides 1 and 2 of the value program card. (It is assumed that the program steps have previously been stored on a card. See page 2.)

**Store the coefficients:**

f CL REG

| | | |
|---|---|---|
| 15.01 | STO | A |
| - 2.178 | STO | B |
| .00512 | STO | D |
| - .14475 | STO | E |
| - .0001147 | STO | 2 |
| - .00002432 | STO | 3 |
| - .00009637 | STO | 4 |
| - .000208 | STO | 5 |
| - .000126 | STO | 6 |

Store the coefficients for the young-growth Douglas-fir lumber value equation in the registers specified in appendix 1, part 2. The coefficients for an individual equation can be stored on a card (see page 2). In that case, simply load the card.

**Run the program:**

| | | |
|---|---|---|
| B | | Initializes the Douglas-fir value equation |
| 24.5 | R/S | D.b.h. (inches) |
| 142 | R/S | Height (feet) |
| 75 | R/S | Height to crown (feet) |
| 3 | R/S | Knot (inches) |
| 10 | R/S | Percent defect |
| 0 | R/S | Basal scar (inches) |

Total tree lumber tally value = $273.68.

## Literature Cited

Fahey, Thomas D. Grading second-growth Douglas-fir by basic tree measurements. J. For. 78(4): 204-206; 1980.

Lane, Paul H.; Plank, Marlin E.; Henley John W. A new and easier way to estimate the quality of inland Douglas-fir sawtimber. Res. Pap. PNW-101. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1970. 9 p.

Plank, Marlin E. Estimating value and volume of ponderosa pine trees by equations. Res. Pap. PNW-283. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1981. 13 p.

Plank, Marlin E.; Snellgrove, Thomas A. An equation for estimating the value and volume of western larch trees. Res. Pap. PNW-231. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1978. 29 p.

Snellgrove, Thomas A.; Plank, Marlin E.; Lane, Paul H. An improved system for estimating the value of western white pine. Res Pap. PNW-166. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1973. 19 p.

# Appendix 1: Information on Species

## Inland Douglas-Fir

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**Part 1.**

| Lumber grade | $/MBF[1] | Percent of volume |
|---|---|---|
| C & Better Select | 671.82 | 0.7 |
| D Select | 512.50 | 1.0 |
| #2 & Better Common | 251.35 | .4 |
| #3 Common | 168.59 | 2.5 |
| #4 Common | 136.22 | 2.3 |
| #5 Common | 82.51 | .5 |
| Select Structural | 278.38 | 9.3 |
| Standard & Better | 237.44 | 56.4 |
| Utility | 156.05 | 19.8 |
| Economy | 74.09 | 7.1 |

Total lumber tally volume = 733,683 board feet.

---

**Part 2.**

| Equation variable | H-P storage register | Volume coefficient | Value coefficient |
|---|---|---|---|
| Y-intercept | STO A | -33.763 | -3.7635 |
| D | STO B | 1.0162 | 1.599 |
| $D^2$ | STO C | - .1247 | - .1536 |
| $D^2H$ | STO D | .01085 | .002349 |
| H | STO E | - .3195 | - .45195 |
| B | STO 1 | - .08339 | - .4944 |
| S | STO 2 | - .5226 | - .2736 |
| DH | STO 4 | .06079 | .04537 |
| P | STO 5 | - .9091 | - .277 |
| $P^2$ | STO 6 | - .004588 | - .00105 |

---

**Part 3.**

| Step | Data input | Press key:[2] |
|---|---|---|
| 1 | — | A |
| 2 | D | R/S |
| 3 | H | R/S |
| 4 | P (or zero) | R/S |
| 5 | S (or zero) | R/S |
| 6 | B (or zero) | R/S |

To repeat, go to step 1.

---

[1] Prices supplied by the USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

[2] The steps are the same for both volume and value.

## Young-Growth Coast Douglas-Fir (Lumber)

---

**Part 1.**

| Lumber grade | $/MBF[3] | Percent of volume |
|---|---|---|
| C & Better Select | 544.24 | 1.7 |
| D Select & Moulding | 473.16 | .3 |
| Shops & Factory Select | 259.83 | .2 |
| Select Structural | 296.70 | 24.5 |
| Construction | 278.28 | 45.3 |
| Standard | 242.97 | 16.8 |
| Utility | 171.80 | 9.0 |
| Economy | 79.17 | 2.2 |

Total lumber tally volume = 222,817 board feet.

---

**Part 2.**

| Equation variable | H-P storage register | Volume coefficient | Value coefficient |
|---|---|---|---|
| Y-intercept | $\boxed{STO}$ $\boxed{A}$ | 61.3 | 15.01 |
| D | $\boxed{STO}$ $\boxed{B}$ | - 8.6935 | - 2.178 |
| $D^2H$ | $\boxed{STO}$ $\boxed{D}$ | .01828 | .00512 |
| H | $\boxed{STO}$ $\boxed{E}$ | - .5325 | - .14475 |
| $K(D^2H)$ | $\boxed{STO}$ $\boxed{2}$ | — | - .0001147 |
| $P(D^2H)$ | $\boxed{STO}$ $\boxed{3}$ | - .0000871 | - .00002432 |
| $S^{1\,2}(D^2H)$ | $\boxed{STO}$ $\boxed{4}$ | - .000285 | - .00009637 |
| $((H-C)/H)\ (D^2H)$ | $\boxed{STO}$ $\boxed{5}$ | - .0003175 | - .000208 |
| $(D^2/H)\ (D^2H)$ | $\boxed{STO}$ $\boxed{6}$ | - .0004725 | - .000126 |

---

**Part 3.**

| Step | Volume data input | Press key: | Value data input | Press key: |
|---|---|---|---|---|
| 1 | — | $\boxed{B}$ | — | $\boxed{B}$ |
| 2 | D | $\boxed{R/S}$ | D | $\boxed{R/S}$ |
| 3 | H | $\boxed{R/S}$ | H | $\boxed{R/S}$ |
| 4 | C | $\boxed{R/S}$ | C | $\boxed{R/S}$ |
| 5 | P (or zero) | $\boxed{R/S}$ | K (or zero) | $\boxed{R/S}$ |
| 6 | S (or zero) | $\boxed{R/S}$ | P (or zero) | $\boxed{R/S}$ |
| 7 | — | — | S (or zero) | $\boxed{R/S}$ |

To repeat, go to step 1.

---

[3] Prices supplied by the USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

**Young-Growth Coast Douglas-Fir (Veneer)**

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**Part 1.**

| Veneer grade | $/M ft$^2$ [4] | Percent of volume |
|---|---|---|
| A | 397.45 | 0.2 |
| B | 391.19 | 4.9 |
| C | 150.75 | 49.4 |
| D | 150.38 | 45.6 |

Total volume (3/8-inch basis) = 179,824 square feet.

---

**Part 2.**

| Equation variable | H-P storage register | Volume coefficient | Value coefficient |
|---|---|---|---|
| $D$ | $\boxed{STO}$ $\boxed{B}$ | -86.039 | -14.38 |
| $D^2$ | $\boxed{STO}$ $\boxed{C}$ | 3.4517 | .6608 |
| $D^2H$ | $\boxed{STO}$ $\boxed{D}$ | .04427 | .006106 |
| $K(D^2H)$ | $\boxed{STO}$ $\boxed{2}$ | — | - .0004559 |
| $P(D^2H)$ | $\boxed{STO}$ $\boxed{3}$ | - .0002302 | - .00002344 |
| $S^{1\ 2}(D^2H)$ | $\boxed{STO}$ $\boxed{4}$ | - .002399 | - .0004998 |
| $((H-C)/H)\ (D^2H)$ | $\boxed{STO}$ $\boxed{5}$ | - .006215 | - .0001437 |
| $(D^2/H)\ (D^2H)$ | $\boxed{STO}$ $\boxed{6}$ | - .002535 | - .0002548 |

---

**Part 3.**

| Step | Volume data input | Press key: | Value data input | Press key: |
|---|---|---|---|---|
| 1 | — | $\boxed{f}$ $\boxed{\ }$ $\boxed{b}$ | — | $\boxed{f}$ $\boxed{\ }$ $\boxed{b}$ |
| 2 | D | $\boxed{R/S}$ | D | $\boxed{R/S}$ |
| 3 | H | $\boxed{R/S}$ | H | $\boxed{R/S}$ |
| 4 | C | $\boxed{R/S}$ | C | $\boxed{R/S}$ |
| 5 | P (or zero) | $\boxed{R/S}$ | K | $\boxed{R/S}$ |
| 6 | S (or zero) | $\boxed{R/S}$ | P (or zero) | $\boxed{R/S}$ |
| 7 | — | — | S (or zero) | $\boxed{R/S}$ |

To repeat, go to step 1.

---

[4] Prices supplied by the USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

## Western White Pine

---

**Part 1.**

| Lumber grade | $/MBF[5] | Percent of volume |
|---|---|---|
| C & Better Select | 888.64 | 5.6 |
| D Select | 655.26 | 7.2 |
| Moulding | 438.78 | 2.9 |
| #3 Clear | 316.41 | 1.8 |
| Shop | 330.71 | 3.5 |
| #1 Common | 499.80 | 1.3 |
| #2 Common | 463.82 | 22.6 |
| #3 Common | 293.08 | 39.0 |
| #4 Common | 183.46 | 13.4 |
| #5 Common | 94.06 | 2.6 |

Total lumber tally volume = 131,724 board feet.

---

**Part 2.**

| Equation variable | H-P storage register | Volume coefficient | Value coefficient |
|---|---|---|---|
| Y-intercept | STO A | -393.0 | -147.099 |
| $D$ | STO B | 88.954 | 38.517 |
| $D^2$ | STO C | - 3.1485 | - 1.5008 |
| $D^2H$ | STO D | .02347 | .01009 |
| $H$ | STO E | - 5.6184 | - 2.5272 |
| $L$ | STO 1 | .4015 | .090 |
| $(H/D)^2$ | STO 2 | 2.2715 | .9355 |
| $P(D^2H)$ | STO 3 | - .00005126 | - .00002092 |
| $P^2(D^2H)$ | STO 4 | - .0000008985 | - .0000004476 |
| $B(D^2H)$ | STO 5 | - .0001316 | - .0001095 |
| $F_{16}(D^2H)$ | STO 6 | - .0003235 | .00002648 |

---

**Part 3.**

| Step | Data input | Press key:[6] |
|---|---|---|
| 1 | — | C |
| 2 | D | R/S |
| 3 | H | R/S |
| 4 | L | R/S |
| 5 | B (or zero) | R/S |
| 6 | $F_{16}$ (or zero) | R/S |
| 7 | P (or zero) | R/S |

To repeat, go to step 1.

---

[5] Prices supplied by the USDA Forest Service, Northern Region, Missoula, Montana.

[6] The steps are the same for both volume and value.

## Ponderosa Pine (Old-Growth)

**Part 1.**

| Lumber grade | \$/MBF[7] | Percent of volume |
|---|---|---|
| C & Better Select | 1,015.00 | 4.4 |
| D Select | 751.00 | 4.4 |
| Moulding | 672.40 | 8.8 |
| #3 Clear | 427.79 | .2 |
| #1 Shop | 425.01 | 6.2 |
| #2 Shop | 318.10 | 20.4 |
| #3 Shop & Shop Out | 322.29 | 14.1 |
| #2 & Better Common | 355.73 | 11.5 |
| #3 Common | 229.12 | 19.7 |
| #4 Common | 169.48 | 8.1 |
| #5 Common | 96.42 | 1.6 |
| Pitchy Select | 751.00 | .6 |

Total lumber tally volume = 130,998 board feet.

**Part 2.**

| Equation variable | H-P storage register | | Volume coefficient | Value coefficient |
|---|---|---|---|---|
| Y-intercept | STO | A | -3.007 | 8.0025 |
| $D^2$ | STO | C | — | - .04757 |
| $D^2H$ | STO | D | .01552 | .007859 |
| H | STO | E | - .8265 | — |
| L | STO | 1 | .4220 | — |
| $F_{32}$ | STO | 1 | — | 15.80 |
| $P(D^2H)$ | STO | 3 | - .00008439 | - .00001319 |
| $P^2(D^2H)$ | STO | 4 | .0000008298 | — |
| DH | STO | 4 | — | - .05932 |
| $A(D^2H)$ | STO | 5 | — | - .0003604 |

**Part 3.**

| Step | Volume data input | Press key: | Value data input | Press key: |
|---|---|---|---|---|
| 1 | — | D | — | D |
| 2 | D | R/S | D | R/S |
| 3 | H | R/S | H | R/S |
| 4 | L | R/S | $F_{32}$ (or zero) | R/S |
| 5 | P (or zero) | R/S | P (or zero) | R/S |
| 6 | — | — | A | R/S |

To repeat, go to step 1.

---

[7] Prices supplied by the USDA Forest Service, Northern Region, Missoula, Montana.

## Western Larch

---

**Part 1.**

| Lumber grade | $/MBF[8] | Percent of volume |
|---|---|---|
| C & Better Select | 671.92 | 7.1 |
| D Select | 512.50 | 7.4 |
| #2 & Better Common | 251.35 | 2.4 |
| #3 Common | 168.59 | 10.2 |
| #4 Common | 136.22 | 7.2 |
| #5 Common | 82.51 | 2.2 |
| Select Structural | 278.38 | 3.5 |
| Standard & Better | 237.44 | 39.1 |
| Utility | 156.05 | 14.7 |
| Ecomony | 74.09 | 6.2 |

Total lumber tally volume = 342,691 board feet.

---

**Part 2.**

| Equation variable | H-P storage register | | Volume coefficient | Value coefficient |
|---|---|---|---|---|
| Y-intercept | STO | A | 80.454 | 2.5682 |
| D | STO | B | — | - .8174 |
| $D^2$ | STO | C | .6770 | - .01769 |
| $D^2H$ | STO | D | .008336 | .003893 |
| H | STO | E | - 5.5433 | .03806 |
| $F_{16}$ | STO | 1 | 2.4064 | 2.5928 |
| $H^2$ | STO | 2 | .03391 | — |
| $P(D^2H)$ | STO | 3 | - .00008872 | - .00003574 |
| $P^2(D^2H)$ | STO | 4 | - .0000004194 | .000000008396 |
| H/D | STO | 5 | 8.9652 | -2.2164 |
| $(H/D)^2$ | STO | 6 | .07783 | — |

---

**Part 3.**

| Step | Data input | Press key:[9] |
|---|---|---|
| 1 | — | E |
| 2 | D | R/S |
| 3 | H | R/S |
| 4 | $F_{16}$ (or zero) | R/S |
| 5 | P(or zero) | R/S |

To repeat, go to step 1.

---

[8] Prices supplied by the USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

[9] The steps are the same for both volume and value.

## ppendix 2: Programs

### alue Program

| | HP 97 | HP 67 |
|---|---|---|
| 001 | *LBL A | f LBL A |
| 002 | GSB 1 | f GSB 1 |
| 003 | RCL 7 | RCL 7 |
| 004 | RCL 8 | RCL 8 |
| 005 | RCL 4 | RCL 4 |
| 006 | x | x |
| 007 | x | x |
| 008 | STO + 0 | STO + 0 |
| 009 | RCL 5 | RCL 5 |
| 010 | R/S | R/S |
| 011 | x | x |
| 012 | STO + O | STO + O |
| 013 | f LASTx | h LSTx |
| 014 | $x^2$ | g $x^2$ |
| 015 | RCL 6 | RCL 6 |
| 016 | x | x |
| 017 | STO + O | STO + O |
| 018 | 2 | 2 |
| 019 | STO I | h STI |
| 020 | GSB 2 | f GSB 2 |
| 021 | RCL 0 | RCL 0 |
| 022 | PRINTx | f -x- |
| 023 | RTN | h RTN |
| 024 | *LBL B | f LBL B |
| 025 | GSB 1 | f GSB 1 |
| 026 | *LBL 3 | f LBL 3 |
| 027 | RCL 8 | RCL 8 |
| 028 | R/S | R/S |
| 029 | - | - |
| 030 | RCL 8 | RCL 8 |
| 031 | ÷ | ÷ |
| 032 | RCL 9 | RCL 9 |
| 033 | x | x |
| 034 | RCL 5 | RCL 5 |
| 035 | x | x |
| 036 | STO + O | STO + O |
| 037 | RCL 2 | RCL 2 |
| 038 | GSB 5 | f GSB 5 |
| 039 | RCL 3 | RCL 3 |
| 040 | GSB 5 | f GSB 5 |
| 041 | RCL 4 | RCL 4 |
| 042 | RCL 9 | RCL 9 |
| 043 | R/S | R/S |
| 044 | $\sqrt{x}$ | f $\sqrt{x}$ |
| 045 | x | x |
| 046 | x | x |
| 047 | STO + O | STO + O |
| 048 | RCL 7 | RCL 7 |
| 049 | $x^2$ | g $x^2$ |
| 050 | $x^2$ | g $x^2$ |
| 051 | RCL 6 | RCL 6 |
| 052 | x | x |
| 053 | STO + O | STO + O |
| 054 | RCL 0 | RCL 0 |
| 055 | PRINTx | f -x- |
| 056 | RTN | h RTN |
| 057 | LBL f b | g LBLf b |
| 058 | GSB 1 | f GSB 1 |
| 059 | GSB 3 | f GSB 3 |
| 060 | RTN | h RTN |
| 061 | *LBL C | f LBL C |
| 062 | GSB 1 | f GSB 1 |
| 063 | 1 | 1 |
| 064 | STO I | h STI |
| 065 | GSB 2 | f GSB 2 |
| 066 | RCL 8 | RCL 8 |
| 067 | RCL 7 | RCL 7 |
| 068 | ÷ | ÷ |
| 069 | $x^2$ | g $x^2$ |
| 070 | RCL 2 | RCL 2 |
| 071 | x | x |
| 072 | STO + O | STO + O |
| 073 | RCL 5 | RCL 5 |
| 074 | GSB 5 | f GSB 5 |
| 075 | RCL 6 | RCL 6 |
| 076 | GSB 5 | f GSB 5 |
| 077 | GSB 4 | f GSB 4 |
| 078 | RCL 0 | RCL 0 |
| 079 | PRINTx | f -x- |
| 080 | RTN | h RTN |
| 081 | *LBL D | f LBL D |
| 082 | GSB 1 | f GSB 1 |
| 083 | 1 | 1 |
| 084 | STO I | h STI |
| 085 | GSB 2 | f GSB 2 |
| 086 | RCL 3 | RCL 3 |
| 087 | GSB 5 | f GSB 5 |
| 088 | RCL 5 | RCL 5 |
| 089 | GSB 5 | f GSB 5 |
| 090 | RCL 7 | RCL 7 |
| 091 | RCL 8 | RCL 8 |
| 092 | x | x |
| 093 | RCL 4 | RCL 4 |
| 094 | x | x |
| 095 | STO + O | STO + O |
| 096 | RCL 0 | RCL 0 |
| 096 | PRINTx | f -x- |
| 098 | RTN | h RTN |
| 099 | *LBL E | f LBL E |
| 100 | GSB 1 | f GSB 1 |
| 101 | 1 | 1 |
| 102 | STO I | h STI |
| 103 | GSB 2 | f GSB 2 |
| 104 | RCL 8 | RCL 8 |
| 105 | RCL 7 | RCL 7 |
| 106 | ÷ | ÷ |
| 107 | RCL 5 | RCL 5 |
| 108 | x | x |
| 109 | STO + O | STO + O |
| 110 | GSB 4 | f GSB 4 |
| 111 | RCL 0 | RCL 0 |
| 112 | PRINTx | f -x- |
| 113 | RTN | h RTN |
| 114 | *LBL 1 | f LBL 1 |
| 115 | RCL A | RCL A |
| 116 | STO O | STO O |
| 117 | RCL B | RCL B |
| 118 | R/S | R/S |
| 119 | STO 7 | STO 7 |
| 120 | x | x |
| 121 | STO + O | STO + O |
| 122 | RCL C | RCL C |
| 123 | f LASTx | h LSTx |
| 124 | $x^2$ | g $x^2$ |
| 125 | x | x |
| 126 | STO + O | STO + O |
| 127 | f LASTx | h LSTx |
| 128 | R/S | R/S |
| 129 | STO 8 | STO 8 |
| 130 | x | x |
| 131 | STO 9 | STO 9 |
| 132 | RCL D | RCL D |
| 133 | x | x |
| 134 | STO + O | STO + O |
| 135 | RCL 8 | RCL 8 |
| 136 | RCL E | RCL E |
| 137 | x | x |
| 138 | STO + O | STO + O |
| 139 | RTN | h RTN |
| 140 | *LBL 2 | f LBL 2 |
| 141 | R/S | R/S |
| 142 | RCL (i) | RCL (i) |
| 143 | x | x |
| 144 | STO + O | STO + O |
| 145 | f DSZ I | f DSZ |
| 146 | GTO 2 | GTO 2 |
| 147 | RTN | h RTN |
| 148 | *LBL 4 | f LBL 4 |
| 149 | RCL 3 | RCL 3 |
| 150 | RCL 9 | RCL 9 |
| 151 | x | x |
| 152 | R/S | R/S |
| 153 | x | x |
| 154 | STO + O | STO + O |
| 155 | f LASTx | h LSTx |
| 156 | $x^2$ | g $x^2$ |
| 157 | RCL 4 | RCL 4 |
| 158 | RCL 9 | RCL 9 |
| 159 | x | x |
| 160 | x | x |
| 161 | STO + O | STO + O |
| 162 | RTN | h RTN |
| 163 | *LBL 5 | f LBL 5 |
| 164 | RCL 9 | RCL 9 |
| 165 | R/S | R/S |
| 166 | x | x |
| 167 | x | x |
| 168 | STO + O | STO + O |
| 169 | RTN | h RTN |

**Volume Program**

| | HP 97 | HP 67 |
|---|---|---|
| 001 | *LBL A | f LBL A |
| 002 | GSB 1 | f GSB 1 |
| 003 | RCL 7 | RCL 7 |
| 004 | RCL 8 | RCL 8 |
| 005 | RCL 4 | RCL 4 |
| 006 | x | x |
| 007 | x | x |
| 008 | STO + 0 | STO + 0 |
| 009 | RCL 5 | RCL 5 |
| 010 | R/S | R/S |
| 011 | x | x |
| 012 | STO + O | STO + O |
| 013 | f LASTx | h LSTx |
| 014 | $x^2$ | g $x^2$ |
| 015 | RCL 6 | RCL 6 |
| 016 | x | x |
| 017 | STO + O | STO + O |
| 018 | 2 | 2 |
| 019 | STO I | h STI |
| 020 | GSB 2 | f GSB 2 |
| 021 | RCL 0 | RCL 0 |
| 022 | PRINTx | f -x- |
| 023 | RTN | h RTN |
| 024 | *LBL B | f LBL B |
| 025 | GSB 1 | f GSB 1 |
| 026 | GSB 3 | f GSB 3 |
| 027 | RTN | h RTN |
| 028 | *LBL f b | g LBLf b |
| 029 | GSB 1 | f GSB 1 |
| 030 | *LBL 3 | f LBL 3 |
| 031 | RCL 8 | RCL 8 |
| 032 | R/S | R/S |
| 033 | - | - |
| 034 | RCL 8 | RCL 8 |
| 035 | ÷ | ÷ |
| 036 | RCL 9 | RCL 9 |
| 037 | x | x |
| 038 | RCL 5 | RCL 5 |
| 039 | x | x |
| 040 | STO + O | STO + O |
| 041 | RCL 3 | RCL 3 |
| 042 | GSB 5 | f GSB 5 |
| 043 | RCL 4 | RCL 4 |
| 044 | RCL 9 | RCL 9 |
| 045 | R/S | R/S |
| 046 | $\sqrt{x}$ | f $\sqrt{x}$ |
| 047 | x | x |
| 048 | x | x |
| 049 | STO + O | STO + O |
| 050 | RCL 7 | RCL 7 |
| 051 | $x^2$ | g $x^2$ |
| 052 | $x^2$ | g $x^2$ |
| 053 | RCL 6 | RCL 6 |
| 054 | x | x |
| 055 | STO + O | STO + O |
| 056 | RCL 0 | RCL 0 |
| 057 | PRINTx | f -x- |
| 058 | RTN | h RTN |
| 059 | *LBL C | f LBL C |
| 060 | GSB 1 | f GSB 1 |
| 061 | 1 | 1 |
| 062 | STO I | h STI |
| 063 | GSB 2 | f GSB 2 |
| 064 | RCL 8 | RCL 8 |
| 065 | RCL 7 | RCL 7 |
| 066 | ÷ | ÷ |
| 067 | $x^2$ | g $x^2$ |
| 068 | RCL 2 | RCL 2 |
| 069 | x | x |
| 070 | STO + O | STO + O |
| 071 | RCL 5 | RCL 5 |
| 072 | GSB 5 | f GSB 5 |
| 073 | RCL 6 | RCL 6 |
| 074 | GSB 5 | f GSB 5 |
| 075 | GSB 4 | f GSB 4 |
| 076 | RCL 0 | RCL 0 |
| 077 | PRINTx | f -x- |
| 078 | RTN | h RTN |
| 079 | *LBL D | f LBL D |
| 080 | GSB 1 | f GSB 1 |
| 081 | 1 | 1 |
| 082 | STO I | h STI |
| 083 | GSB 2 | f GSB 2 |
| 084 | GSB 4 | f GSB 4 |
| 085 | RCL 0 | RCL 0 |
| 086 | PRINTx | f -x- |
| 087 | RTN | h RTN |
| 088 | *LBL E | f LBL E |
| 089 | GSB 1 | f GSB 1 |
| 090 | RCL 8 | RCL 8 |
| 091 | $x^2$ | g $x^2$ |
| 092 | RCL 2 | RCL 2 |
| 093 | x | x |
| 094 | STO + O | STO + O |
| 095 | RCL 5 | RCL 5 |
| 096 | RCL 8 | RCL 8 |
| 097 | RCL 7 | RCL 7 |
| 098 | ÷ | ÷ |
| 099 | x | x |
| 100 | STO + O | STO + O |
| 101 | f LASTx | h LSTx |
| 102 | $x^2$ | g $x^2$ |
| 103 | RCL 6 | RCL 6 |
| 104 | x | x |
| 105 | STO + O | STO + O |
| 106 | 1 | 1 |
| 107 | STO I | h STI |
| 108 | GSB 2 | f GSB 2 |
| 109 | GSB 4 | f GSB 4 |
| 110 | RCL 0 | RCL 0 |
| 111 | PRINTx | f -x- |
| 112 | RTN | h RTN |
| 113 | *LBL 1 | f LBL 1 |
| 114 | RCL A | RCL A |
| 115 | STO O | STO O |
| 116 | RCL B | RCL B |
| 117 | R/S | R/S |
| 118 | STO 7 | STO 7 |
| 119 | x | x |
| 120 | STO + O | STO + O |
| 121 | RCL C | RCL C |
| 122 | f LASTx | h LSTx |
| 123 | $x^2$ | g $x^2$ |
| 124 | x | x |
| 125 | STO + O | STO + O |
| 126 | f LASTx | h LSTx |
| 127 | R/S | R/S |
| 128 | STO 8 | STO 8 |
| 129 | x | x |
| 130 | STO 9 | STO 9 |
| 131 | RCL D | RCL D |
| 132 | x | x |
| 133 | STO + O | STO + O |
| 134 | RCL 8 | RCL 8 |
| 135 | RCL E | RCL E |
| 136 | x | x |
| 137 | STO + O | STO + O |
| 138 | RTN | h RTN |
| 139 | *LBL 2 | f LBL 2 |
| 140 | R/S | R/S |
| 141 | RCL (i) | RCL (i) |
| 142 | x | x |
| 143 | STO + O | STO + O |
| 144 | f DSZ I | f DSZ |
| 145 | GTO 2 | GTO 2 |
| 146 | RTN | h RTN |
| 147 | *LBL 4 | f LBL 4 |
| 148 | RCL 3 | RCL 3 |
| 149 | RCL 9 | RCL 9 |
| 150 | x | x |
| 151 | R/S | R/S |
| 152 | x | x |
| 153 | STO + O | STO + O |
| 154 | f LASTx | h LSTx |
| 155 | $x^2$ | g $x^2$ |
| 156 | RCL 4 | RCL 4 |
| 157 | RCL 9 | RCL 9 |
| 158 | x | x |
| 159 | x | x |
| 160 | STO + O | STO + O |
| 161 | RTN | h RTN |
| 162 | *LBL 5 | f LBL 5 |
| 163 | RCL 9 | RCL 9 |
| 164 | R/S | R/S |
| 165 | x | x |
| 166 | x | x |
| 167 | STO + O | STO + O |
| 168 | RTN | h RTN |

Sachet, Janet K. Ayer. Programable calculator programs to solve softwood volume and value equations. Gen. Tech. Rep. PNW-143. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 12 p.

This paper presents product value and product volume equations as programs for handheld calculators. These tree equations are for inland Douglas-fir, young-growth Douglas-fir, western white pine, ponderosa pine, and western larch. Operating instructions and an example are included.

Keywords: Mathematical programing, calculators, volume estimation, timber value.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

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Pacific Northwest Forest and Range
Experiment Station
809 NE Sixth Avenue
Portland, Oregon 97232

United States
Department of
Agriculture

**Forest Service**

Pacific Northwest
Forest and Range
Experiment Station

General Technical
Report
PNW-144

September 1982

# Indicators of Cull in Western Oregon Conifers

Paul E. Aho

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PAUL E. AHO is a research plant pathologist, Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331.

## Abstract

Aho, Paul E. Indicators of cull in western Oregon conifers. Gen. Tech. Rep. PNW-144. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 17 p.

Descriptions and color photographs of important fungal sporophores (conks), other indicators of cull (wounds), and associated decays in western Oregon conifers are provided to aid timber markers, cruisers, and scalers in identifying them. Cull factors are given for the indicators by tree species.

Keywords: Cull logs, decay (wood), timber cruising, log scaling, coniferae, western Oregon.

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## Introduction

Timber cruisers and scalers must be able to estimate net volumes of standing trees and bucked logs accurately. Accurate inventories are essential to sustained-yield forestry. Forest land is classified, timber is sold, roads are built, and mills are developed from estimates of net volume obtainable from a given acreage of forest land. Serious financial losses can occur when less volume is harvested than cruisers report.

Cruisers and scalers need to recognize indicators of decay and other defects on logs and trees to predict net volumes accurately. Sporophores or conks of decay fungi are the most important indicators of decay in standing trees or logs. Amount of decay associated with conks depends on the species of fungus producing the conk. Fortunately, only a few fungi are responsible for most decay losses in western Oregon conifers.

Decay in trees is caused primarily by two classes of fungi, white rot and brown rot. White-rot fungi produce enzymes that can use all wood components; brown-rot fungi principally decompose cellulose. Wood with incipient (early) white-rot decay can usually be used for pulpwood and lower grade wood products. Wood in any stage of brown-rot decay cannot be used for pulp or lumber.

Indications that conks have been present or are developing are also useful in predicting presence and amount of decay. Pieces of old conks may still be attached or lying at the base of a tree. A hole in the bark may be where a branch has rotted out or where a conk was attached. Punk and swollen knots are produced commonly by some fungi, and these indicators are especially helpful to scalers. Most sporophores growing from the ground have no relation to decay in living trees, but an important exception is red-brown butt rot.[1] Conks of this fungus, reliable indicators of butt rot, are seldom found on living trees, but are commonly found on the ground at the base of trees with butt rot.

Type and age of all kinds of wounds can be used to determine presence and amount of decay in trees. Basal and trunk wounds, frost cracks, and top damage — such as dead or broken tops, forks, and crooks — are often excellent indicators of defect. Some abnormalities commonly seen on trees are seldom, if ever, associated with decay. Burls, closed dwarf mistletoe and rust cankers on the bole, and bark abnormalities not associated with wound callusing are examples. Infrequent or minor indicators of decay include recent (young) or small (less than 1 foot long) basal or trunk wounds, dead vertical branches, and open dwarf mistletoe and rust bole cankers.

The purpose of this paper is to help timber cruisers and scalers identify indicators of cull[2] and important decays found in the conifer species in western Oregon. Cull factors, if available, will also be given for important indicators on various tree species. Results of numerous studies on decay in Pacific Northwest conifers indicate that decay losses within and among tree species vary considerably from one locality to another and, to an even greater extent, from one region to another. Cull factors for a given tree species should be applied only to that species and only in the locality or area where the cull study was conducted. Because decay is so variable, familiarity with local conditions must be gained by observing cruised timber after it is felled and bucked, by observing decayed logs as they are opened by headsaws, and by comparing cruise estimates with gross and net log scales. The cull rules presented are averages for a tree species and usually are applicable in a limited area. They should be modified only when local knowledge or experience indicate that other cull deductions would be more appropriate.

## Defect Indicators

Two general types of defect indicators are:

- Signs of decay fungi, such as fruiting bodies (conks, sporophores) and punky or swollen knots; and
- Injuries or wounds that are potential infection courts for decay fungi, including basal and trunk wounds, frost cracks or seams, rust and dwarf mistletoe bole cankers, and top damage, such as dead and broken tops, forks, and crooks.

Signs of decay fungi, especially conks, usually indicate that decay is present. Whether or not swollen knots, especially those on Douglas-firs and western hemlocks, are of fungal origin is sometimes difficult to determine, however. Decay is not always associated with injuries. Large, old wounds are most likely to be infected with decay fungi, and associated decay columns are also larger. Some types of indicators seldom have associated decay.

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[1] Scientific names of all taxa mentioned in this paper are given in appendix table 3.

[2] Cull includes decay, shake, and frost cracks. Defect, as used in this paper, is synonymous with cull.

# Decay Fungi

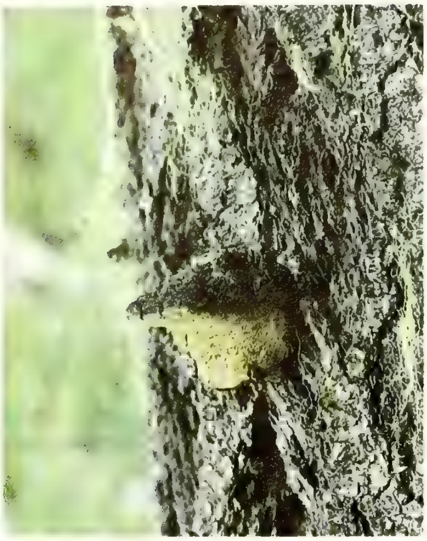


Figure 1. — Conk of red ring rot on the trunk of a Douglas-fir.

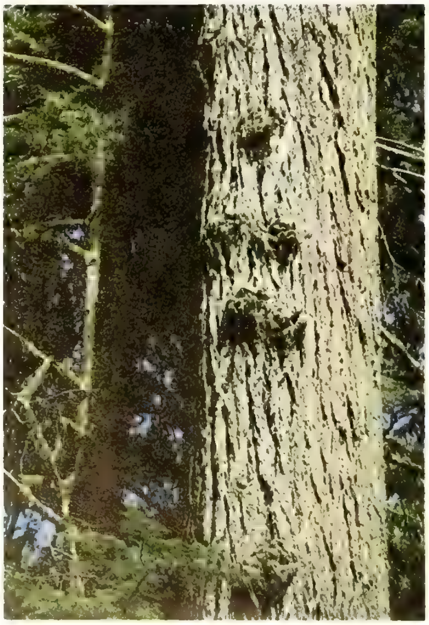


Figure 2. — Swollen knots caused by red ring rot on the trunk of a Douglas-fir.

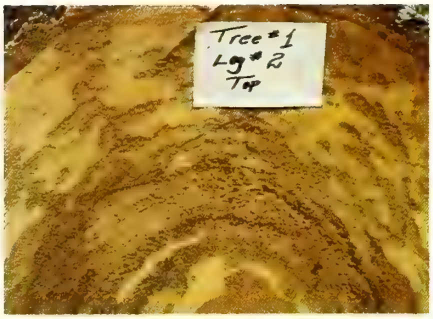


Figure 3. — Decay in a Douglas-fir caused by red ring rot.

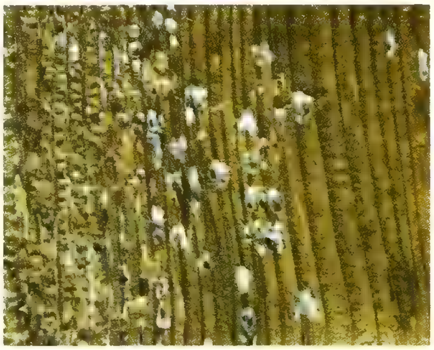


Figure 4. — Close-up of red ring rot decay showing white pockets (white speck).

The first two fungi mentioned are the most commercially important causes of cull; the order in which the others are mentioned has no significance.

## Red Ring Rot

Common names

For the decay: Red ring rot, conk rot, white pocket rot, pecky rot, white speckled rot.

For the fungus: Ring-scale fungus.

Hosts: Douglas-fir, larch, pines, hemlock, spruces, cedar, true firs, and Port-Orford-cedar.

Entry: Thought to be dead branches or stubs.

Location: Trunk.

Conks: Perennial, produced at branch stubs and knots, rarely at wounds. Conks bracketlike to hoof shaped, with a brownish-black upper surface having concentric furrowed rings and a brown undersurface.

Rot: A cellulose and lignin-destroying white pocket rot attacking heartwood. Occasionally enters living sapwood. Can be confused with red ray rot, and red root and butt rot.

Early stage: Usually reddish but varies by host species; usually red-purple in Douglas-fir, light purplish-gray in spruce, pink to reddish in pines, colorless in cedar.

Late stage: Few to many spindle-shaped, white pockets with firm wood between. Pockets may run together; sometimes black zone lines are produced. Late stage may be distributed uniformly, may be in rings, or in crescent-shaped segments of rings.

Key idenfitying features:

- Swollen knots on logs;
- Punk knots on logs;
- White pockets in rot;
- Conks (when present);
- Rot column in rings or crescent-shaped segments of rings; and
- Conks on ground at base of tree.

Cull rules:

Tables 1 and 2 give cruising cull rules for Douglas-fir, western hemlock, and western white pine. Information helpful for modifying the cull deductions is:

- Conk rot is usually more severe:
  From north to south in Oregon;
  In older stands;
  In pure stands than in mixed;
  On steep slopes than on gentle;
  On shallow than deep soils; and
  On sites predominated by secondary vegetation — vine maple, vanillaleaf, oxalis, or rose, rather than salal, twinflower, or rhododendron.
- Conks are higher on trees in older stands.
- The larger the conk, the more related decay — unless the small conks are remnants of large conks that have fallen off.

**Table 1 — Cruising cull rules for red ring rot in Douglas-fir, western hemlock, and western white pine**

| Tree and age | Visible indicator | Deduction |
|---|---|---|
| Douglas-fir | | |
| Under 125 years | Conk | Degrade, but no cull |
| Over 125 years | Conk | See table 2 |
| | Swollen knots | See table 2 |
| Old-growth western hemlock, true firs (over 125 years) | Conks | Cull 16 feet for single conk; 16 feet above and below for group of conks |
| | Swollen knots | Cull 1/2 the distance figured for conks |
| Western white pine | Conks | Cull 2 feet above and 4 feet below each conk |

**Table 2 — Conk deduction in feet above the highest or below the lowest conk for Douglas-firs**

| Tree age | Conks | | Swollen Knots | |
|---|---|---|---|---|
| | Below lowest | Above highest | Below lowest | Above highest |
| Years | | | | |
| 150 | 4 | 4 | 2 | 2 |
| 200 | 10 | 10 | 5 | 5 |
| 250 | 13 | 13 | 7 | 7 |
| 300 | 18 | 18 | 9 | 9 |
| 350 | 22 | 22 | 11 | 11 |

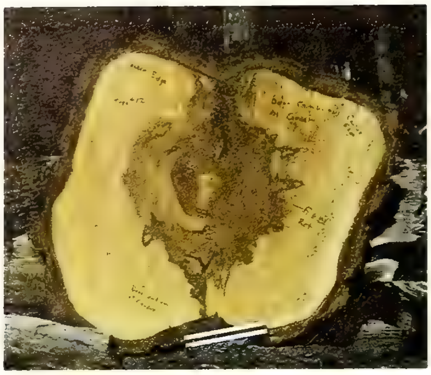


Figure 5. — Cross section from a white fir showing conks, cankers, and decay of red ring rot (var. *cancriformans*).

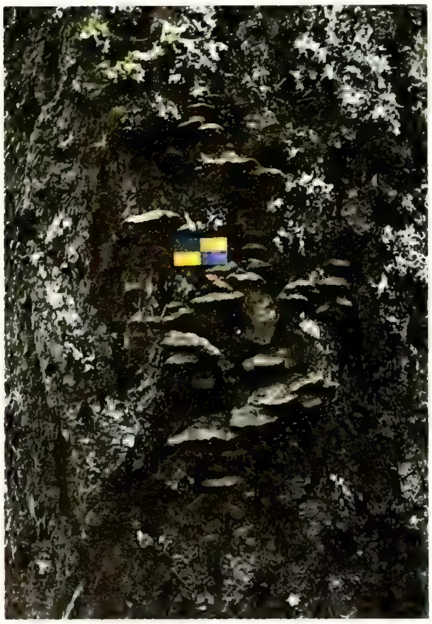


Figure 6. — Red ring rot (var. *cancriformans*) conks on cankered area of a white fir.

## Red Ring Rot (var. *cancriformans*)

Common names:

For the decay: Red ring rot, conk rot, white pocket rot, pecky rot.

For the fungus: Butterfly conk, ring-scale fungus.

Hosts: Grand fir, white fir, California red fir, noble fir, Pacific silver fir, subalpine fir.

Entry: Thought to be dead branches and stubs.

Location: Butt and trunk.

Conks: Conks appear annual but are actually perennial, produced profusely over the surface of cankered areas, usually at the butt of tree rather than at branch stubs and whorls. Bracketlike, with rough upper surface and furrows, 1/2 to more than 3 inches wide. Dull grayish or brownish. In growing conks, lower margin velvety, light golden brown.

Rot: A cellulose- and lignin-destroying white pocket rot attacking sapwood and heartwood, often killing the cambium which causes cankered areas.

Early stage: Light yellow to light brown.

Late stage: Few to many spindle-shaped pockets with firm wood between. Pockets may run together and may be filled with white, yellow, or brown material. Late stage may be uniformly distributed, may be in rings, or in crescent-shaped segments of rings.

Key identifying features:

- Sunken cankered areas;
- Conks (when present) scattered profusely over cankered areas;
- No swollen knots present; and
- Rot column in rings or crescent-shaped segments of rings.

Cull rules:

For white or red fir in southwestern Oregon, deduct 4 feet below the bottom of the lowest canker or conk and 6 feet above the top of the highest.

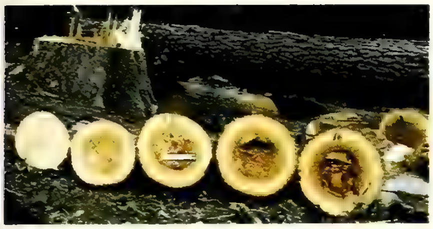


Figure 7. — Cross sections from a white fir showing Indian paint fungus conks and decay.

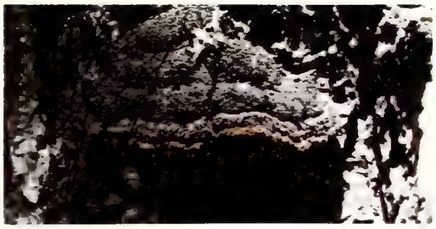


Figure 8. — Indian paint fungus conk on a grand fir.

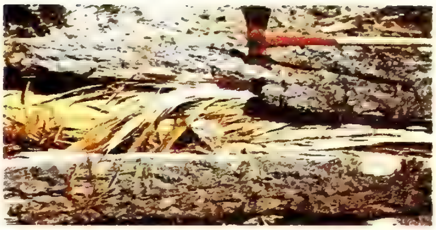


Figure 9. — Felled white fir that split, showing stringy nature of decay from rust-red stringy rot.

## Rust-Red Stringy Rot

Common names:

For the decay: Rust-red stringy rot, brown stringy rot.

For the fungus: Indian paint fungus.

Hosts: True firs and hemlocks, rare in other conifers.

Entry: Dead twigs less than 2 millimeters in diameter.

Location: Trunk.

Conks: Perennial conks hoof shaped, hard and woody; upper surface rough, black, furrowed, and cracked; lower surface covered with coarse, hard grayish spines (teeth). Interior brilliant rust red and brick red. Conks may be confused with those of red ring rot at a distance.

Rot: A brown, stringy rot causing heartwood decomposition of lignin and, to a lesser estent, cellulose. Rot column frequently extensive.

Hidden stage: Wood can be affected seriously before discoloration or texture change is evident. Spring wood is weakened so that it separates during seasoning, producing the defect known as ring shake. Hidden stage may extend up to 5 feet beyond evidence.

Early stage: Softening of wood with a light yellow to brown or water-soaked stain, gradually deepening to pale reddish-brown. Fine rusty-red or even blackish lines may appear in early stage. Some crescent-shaped rings may form.

Late stage: Distinct brownish, reddish-brown, or rusty-red, very soft, and finally reduced to a brown, fibrous, stringy mass. Brown to reddish zone lines often found. Sometimes white patches evident. Logs may be hollow where presence of rot is long standing.

Key identifying features:

- Conks (when present);
- Stringy, fibrous rot; and
- Rusty punk knots on logs (not swollen).

**Cull rules: These cruising cull rules can be applied to rust-red stringy rot on white and red fir in southwestern Oregon.**

| To estimate defect when: | Deduct: |
|---|---|
| Conk is single, small, young | 8 feet above and below conk |
| Lowest conk is 0 to 32 feet from ground | 12 feet below conk: 21 feet above highest conk |
| Lowest conk is more than 32 feet from ground | 20 feet below lowest conk: 21 feet above highest conk |
| Conks are in bottom third of tree | Middle and bottom third |
| Conks are in top third of tree | Top and middle third |
| Two or more conks are separated by 25 feet or more | Entire tree |

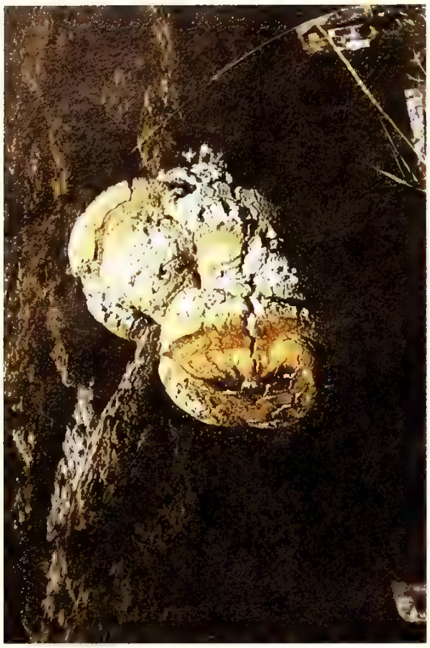


Figure 10. — Brown trunk rot conk on Douglas-fir.

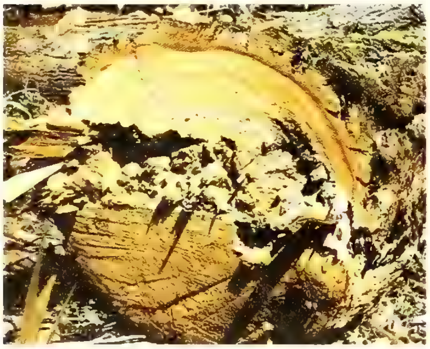


Figure 11. — Conk and decay from brown trunk rot on Douglas-fir.

## Brown Trunk Rot

Common names:

For the decay: Brown trunk rot, red-brown heartrot.

For the fungus: Quinine fungus, chalky fungus.

Hosts: Douglas-fir, ponderosa and sugar pines, larch, and sometimes other western conifers.

Entry: Branch stubs, wounds, broken tops.

Location: Trunk.

Conks: Rare, but unmistakable; Hard, perennial, and hoof shaped, becoming long and cylindrical after several years of development; at branch stubs or on wounds. Conks chalky white to grayish; surface ridged and extensively cracked. Conks soft and white inside, with a bitter flavor; hence the name "quinine fungus."

Rot: A brown, cubical, heartwood rot of top and trunk. Closely resembles brown cubical rot, accurate diagnosis often difficult. Quinine fungus rare in the butt; mostly brown cubical rot there. Thick, bitter-tasting mycelium in quinine fungus; mycelium of brown cubical rot thinner and not bitter.

Early stage: Frequently difficult to detect, color varies by host species. In Douglas-fir, coloration ordinarily not evident, but may be a brilliant purplish; color in ponderosa pine commonly red-brown or brown.

Late stage: Wood breaks down into a crumbly mass of yellow-brown to reddish-brown cubical chunks.

Mycelium: In the late stage, thick, whitish mycelial felts common in shrinking cracks between cubes. Felts may become one-quarter of an inch thick and cover several square feet in a continuous sheet. Felts have characteristic bitter taste and resinous pockets or resinous crusty areas.

## Red-Brown Butt Rot

Common names:

For the decay: Red-brown butt rot, red-brown rot.

For the fungus: Velvet-top fungus.

Hosts: Douglas-fir, pines, spruce, larch, hemlock, western redcedar, true firs.

Entry: Roots (basal scars).

Location: Butt and roots.

Conks: Annual, moist and cheesy when fresh; upper surface reddish brown, velvety with concentric rings and a light yellow margin. Die after a few weeks and become corky, leathery, and dark. Occur as thin brackets at tree base or as irregular saucers on nearby ground.

Rot: A cellulose-destroying, brown, cubical heartwood rot, commonly extending 2 to 10 feet above ground; rot column generally conical.

Early stage: Usually difficult to detect. Occurs as yellowish discoloration extending longitudinally an average of 2 feet beyond visibly decayed wood. Wood becomes soft and cheesy just before typical late stage is reached.

Late stage: Wood becomes soft, brittle, and breaks into large irregular cubes easily crumbled between fingers; reddish brown. Often has odor of turpentine.

Mycelium: Very thin mycelial layers, resembling crusts of resinous material, in shrinkage cracks between cubes.

Key identifying features:

- In butt log (swollen from ground up to 12 feet);
- Conks (when present);
- Cubes in late stage of rot; and
- Very thin mycelial felts between cubes.

Cull rules:

If the conk is found on a scar at the base of Douglas-fir and western hemlock or at the ground, deduct 8 feet of the butt log for young growth, and 16 feet of the butt log for old growth (8 feet on the Umpqua National Forest). If the conk is found on a scar 8 feet or more above the ground, deduct 32 feet.

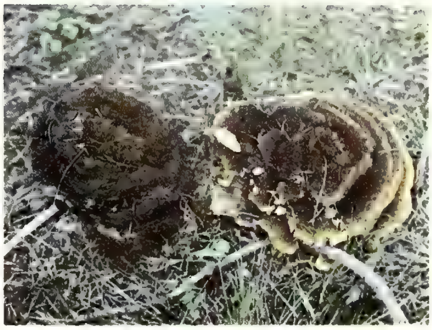


Figure 12. — Old (left) and young (right) conks of red-brown butt rot, on the ground near the base of a tree.

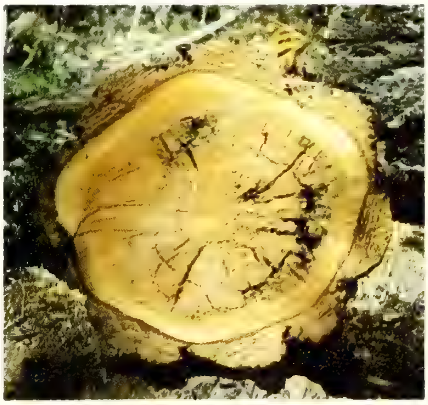


Figure 13. — Red-brown butt rot associated with an old basal wound, in Douglas-fir.

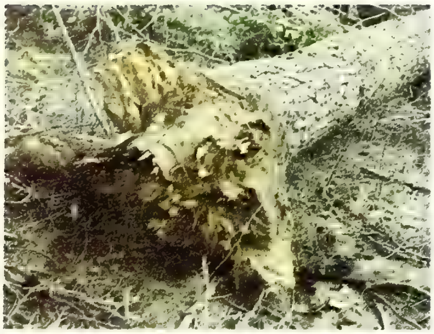


Figure 14. — The root wad of a windthrown grand fir badly infected with yellow laminated rot.

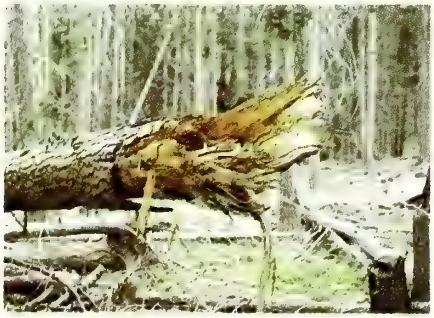


Figure 15. — Yellow laminated rot in a grand fir.

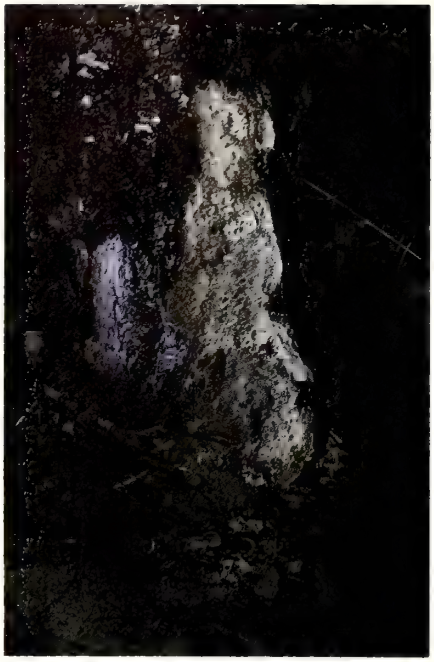


Figure 16. — Sporophore of yellow laminated rot at the base of a Douglas-fir.

## Yellow Laminated Rot

Common names:

For the decay: Yellow laminated rot, yellow ring rot, paper rot, laminated root rot.

For the fungus: Brown cedar poria.

Hosts: Western redcedar, hemlocks, true firs, Douglas-fir, Engelmann spruce, western larch, pines.

Entry: Primarily roots contacting infected roots and stumps.

Location: Butt and roots.

Conks: Seldom found on living trees. Develop under roots, in root crotches, and in basal scars, and on undersides of logs. Perennial, dark chocolate brown, in flat, crust-like layers about one-quarter of an inch thick, generally inconspicuous.

Rot: A white butt rot attacking lignin and springwood more readily than summerwood.

Early stage: Appears as a yellowing of the normal reddish-brown heartwood; the wood remains firm at first, but gradually darkens and softens; radial cracks form on drying.

Late stage: Wood becomes yellow brown to brownish and separates along annual rings, forming thin, papery layers. The thin layers have small elliptical pits parallel to the grain. On ends of logs, rot column may be crescent shaped at first but becomes uniformly circular as the decay develops.

Mycelium: Brownish strands of mycelial threads (setal hyphae) appear between laminated layers and in the elliptical pits.

Key identifying features:

- Separation of annual rings (lamination);
- Brown mycelial threads (setal hyphae); and
- In butt log.

Cull rules:

No cull rules have been established for yellow laminated rot. In Douglas-fir, decay seldom extends more than 5 to 6 feet above the ground. Stand openings with windthrown trees along the edge may indicate presence of the fungus within adjacent living trees.

## White Spongy Rot

Common names:

For the decay: White spongy rot, annosus root rot, fomes root rot, spongy sap rot, white pocket rot, white stringy rot.

Hosts: Western hemlock, white pine, ponderosa pine, and other western conifers.

Entry: Roots and scars.

Location: Butt and roots.

Conks: Perennial, woody to leathery; develop on the lower side of living roots and root crotches, not easily seen. Usually thin, irregularly shaped, mainly occur as flat brown crusts, but sometimes bracketlike. White pore surface frequently incorporates litter into conk.

Rot: A white root and butt rot that decomposes lignin and, to a lesser extent cellulose, in both heartwood and sapwood.

Early stage: Appears as a pinkish to reddish-brown stain; wood firm.

Late stage: White fiber-filled pockets develop in affected sapwood or heartwood and eventually coalesce; wood separates at rings and finally becomes a white, stringy, spongy mass of fibers interspersed with black flecks of mycelium. Eventually wood may be destroyed and a hollow develop.

Key identifying features:

- In butt log;
- Frequently extends into sapwood;
- Black flecks in mycelium;
- Separation at annual rings; and
- Conks.

Cull rules:

For hemlocks, spruce, and some true firs, cull 16 feet of butt log if a conk occurs near the root collar and 4 feet above and below an infected wound.

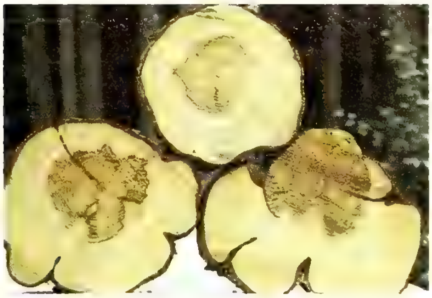


Figure 17. — Decay from white spongy rot associated with a bear wound in western hemlock.

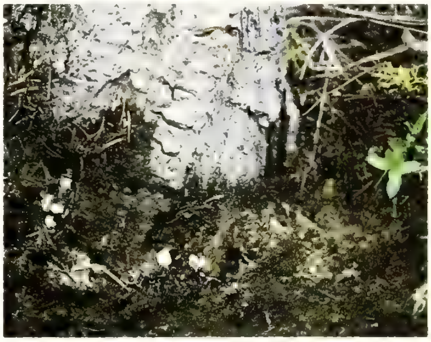


Figure 18. — White spongy rot sporophores at the base of a white fir.

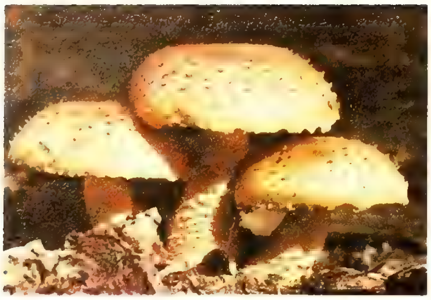


Figure 19. — Sporophores from mottled rot.

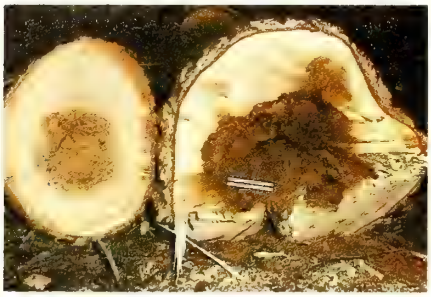


Figure 20. — Decay caused by mottled rot in white fir.

## Mottled Rot

Common names:

For the decay: Mottled rot, brown mottled rot, yellow heartrot.

For the fungus: Yellow cap fungus.

Hosts: True firs, hemlock, white pine, spruce.

Entry: Trunk and basal wounds, dead and broken tops, branch stubs.

Location: Butt, trunk, and tops.

Conks: Gilled mushroom, rather than a conk. Mushrooms annual, fleshy, yellow on upper surface, sticky when wet, stems yellow, gills yellowish to brown. Develop singly in close groups from a common base. Appear in fall sometimes on living trees but mostly on snags, windfalls, or stumps, lasting only a few weeks.

Rot: May be confused with brown stringy rot caused by the Indian paint fungus.

Early stage: Light yellowish color in small areas of heartwood.

Late stage: Discolored areas enlarge and darken to honey color, and brown streaks appear, producing the mottled appearance that gives the rot its common name. Wood breaks up in the last stages after separation at annual rings, finally becoming hollow.

Mycelium: Threads consist of many parallel strands. When wood is split or cut fine, holes are left in the wood where strands are pulled out.

Key identifying features:

- Mushrooms (when present); and
- Mottled.

Cull rules:

The main infection courts for this fungus are wounds, particularly basal wounds. Use cull rules for wounds if available, because fruiting occurs infrequently. For white and red fir in southwestern Oregon, deduct 1 foot below the bottom and 2 feet above the top of the wound.

## Yellow Pitted Rot

Common names:

For the decay: Yellow pitted rot, long pitted rot, long pocket rot.

For the fungus: Fir hydnum, coral fungus.

Hosts: Grand and subalpine firs, Engelmann spruce, hemlock.

Entry: Wounds, dead branches.

Location: Mostly butt log, but not necessarily confined to that section.

Conks: Coral-like, white to cream, soft, annual conks produced on old logs or dead, fallen trees; occasionally on living trees at wounds. Conks characterized by open branching habit and formation of many spines or teeth; fleshy, short lived.

Rot: A white pocket or pitted heartwood rot in living trees and common in stumps, snags, and fallen trees; continues to develop in stored logs.

Early stage: Rot remains firm, appears as a yellowish to brownish discoloration with scattered darker spots, giving affected wood a mottled appearance. Pattern at end of logs generally irregular.

Late stage: Forms elongated pits (pockets) about one-half of an inch long; pits may contain yellowish to white fibers or may be hollow and separated by firm, reddish-brown wood. Similar to red ring rot, but pits longer with blunt ends.

Key identifying features:

- Large pockets with blunt ends; and
- Scattered dark flecks in rot column.

Cull rules:

The main infection courts for this fungus are wounds, particularly basal wounds. Use cull rules for wounds if available, because fruiting bodies occur infrequently. For white and grand fir in southwestern Oregon, deduct 1 foot below the bottom and 2 feet above the top of the wound.

## Brown Crumbly Rot

Common names:

For the decay: Brown crumbly rot.

For the fungus: Red belt fungus, scavenger fungus.

Hosts: Attacks all important conifers, principally larch, hemlock, true firs, and Douglas-fir.

Entry: In living trees, through wounds or dead tops.

Location: Variable; in living trees, around wounds.

Conks: Conks unmistakable; one of the most commonly seen species of wood-decay fungi. Perennial, hard, tough, and hoof to shelf shaped. Upper surface smooth, zoned in gray to black, with a reddish band just inside a white wavy margin.

Rot: Principally a cellulose-destroying brown rot. Very important as a slash rot. Decay in living trees uncommon in the Northwest. Very harmful in deterioration of salvable, killed timber, down trees, and stored logs. Attacks sapwood rapidly, then progresses into heartwood.

Early stage: May appear as a faint brown to yellow-brown stain.

Late stage: Light reddish brown, forming a crumbly mass broken into rough, rather small cubes. Small patches of lighter color may give a mottled appearance on end of log.

Mycelium: Mycelial felts form in shrinkage cracks. Felts are thicker than most similar rots, but not as thick as quinine fungus. Unlike the velvet-top fungus, they are nonresinous.

Key identifying features:

- Brown cubes in late stage;
- Usually in old logs or logs from dead trees;
- Sapwood as well as heartwood affected; and
- Conks (when present).

Cull rules:

No cull rules have been established. Brown crumbly rot usually occurs only on dead wood. If on a living tree, it usually occurs on the face of a wound.

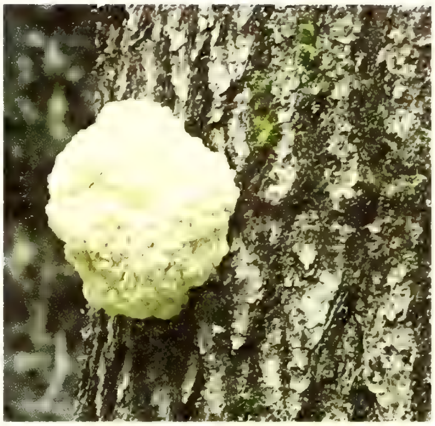


Figure 21. — Sporophore from yellow pitted rot on grand fir.

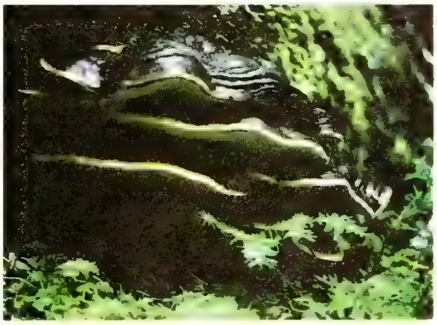


Figure 22. — Sporophores from brown crumbly rot on a western hemlock.

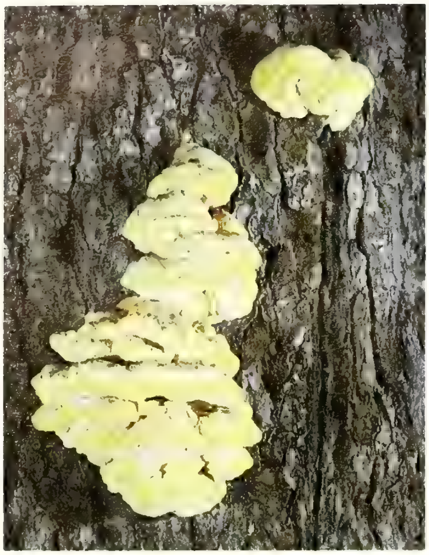


Figure 23. — Sporophore from brown cubical rot.

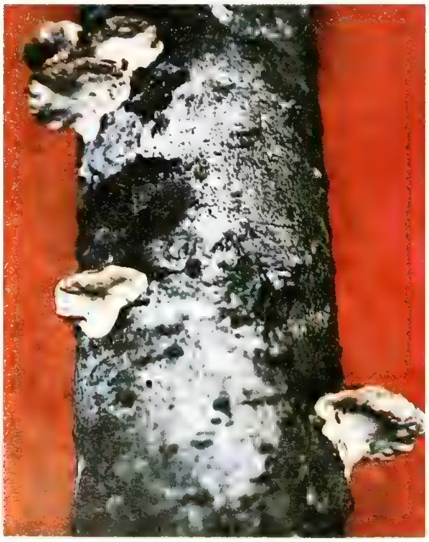


Figure 24. — Sporophore from brown top rot on Douglas-fir.

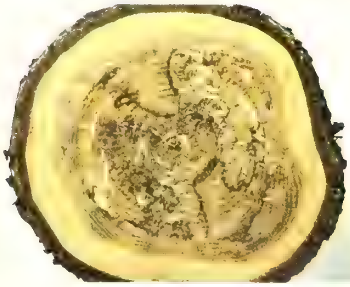


Figure 25. — Brown top rot in Douglas-fir.

## Brown Cubical Rot

Common names:

For the decay: Brown cubical rot, red-brown heartrot.

For the fungus: Sulphur fungus, chicken-of-the-woods.

Hosts: Douglas-fir, white and ponderosa pines, true firs, larch, hemlock, and spruce.

Entry: Wounds, branch stubs.

Location: Sometimes trunks, generally butts.

Conks: Conks one of the most conspicuous of all wood-decay fungi; many often appear in fall on wounds at or near the base of living trees, on stumps, and on fallen logs. Annual, brilliant orange to red orange above and sulphur yellow below. Generally thin and broad, with several parts one above another; edges wavy.

Rot: A cellulose-decomposing, heartwood and occasionally sapwood, brown, cubical rot with mycelial felts. Can be confused with brown trunk rot, red-brown butt rot, or brown crumbly rot.

Hidden stage: Hidden stage usually present; detectable only by microscopic or cultural study.

Early stage: Appears as a light-brown stain.

Late stage: A dark reddish-brown decay breaking into medium-sized irregular cubes. May look rippled in longitudinal section. Cracks of cubes are often completely filled with white mycelial felts plainly evident in cross section, appearing as a network. These felts do not have resin pockets like brown trunk rot (quinine fungus) nor resinous crusts like red-brown butt rot (velvet-top fungus).

Key identifying features:

- A brown cubical rot;
- Generally in butt rather than trunk;
- Conks (rare on logs); and
- Mycelial felts, if typical.

Cull rules:

No cull rules have been established.

## Brown Top Rot

Common names:

For the decay: Brown top rot.

For the fungus: Rose-colored conk.

Hosts: Douglas-fir, grand fir, larch, lodgepole and white pines, spruce, and other western conifers.

Entry: Broken tops (branch stubs).

Location: Upper trunk.

Conks: Delicate, rose-colored undersurface and inner tissue; perennial, woody, bracketlike to hoof shaped; usually appear in a shelving arrangement. Upper surface brown to black, usually cracked and roughened.

Rot: A brown, cubical heartwood rot in living trees, often limited to the top log or unmerchantable top. Frequently found in dead trees, both standing and down; develops rapidly. May continue to develop in wood in service; important in piled logs and pulpwood.

Hidden stage: Wood often moderately affected before discoloration or texture change becomes evident.

Early stage: A faint brownish or yellow-brown stain, outer limits sometimes marked by a greenish-brown zone line.

Late stage: Yellowish to reddish brown, soft, irregularly broken into cubes.

Mycelium: Thin mycelial felts, which vary from white to faint rose-colored, often develop in the cracks between cubes.

Key identifying features:

- Upper trunk and tops;
- Conks (when present);
- Mycelium; and
- Dead or broken tops.

Cull rules:

Conks are difficult to see at the tops of trees. The best indicator is usually the dead or broken top which may be on the ground. For Douglas-fir and hemlocks with conks or a broken top, deduct 16 feet below the indicator.

### Pencil Rot

Common names:

For the decay: Pencil rot, pecky rot, pocket dry rot, pecky cedar, pine rot, incense-cedar dry rot.

For the fungus: Incense-cedar fungus.

Hosts: Incense-cedar, some true firs.

Entry: Fire and other wounds and branch stubs.

Location: Butt and bole.

Conks: Annual sporophores at knots, usually in the summer or autumn; rare. Conks bracket shaped with rounded tops or half-bell shaped. Young conks soft and mushy with a smooth, tan top and a bright sulphur-yellow undersurface with numerous small tubes that sometimes exude clear drops of a yellow, sweet liquid. With age, conks become tough and cheesy, turning brown and finally hard and dry. Last stage rare because insects, birds, and squirrels destroy the conk. A shot-hole cup forms at and below the knot where a conk destroyed by insects or birds had been attached.

Rot: A typical brown cubical rot that attacks cellulose and forms pockets separated by apparently sound wood.

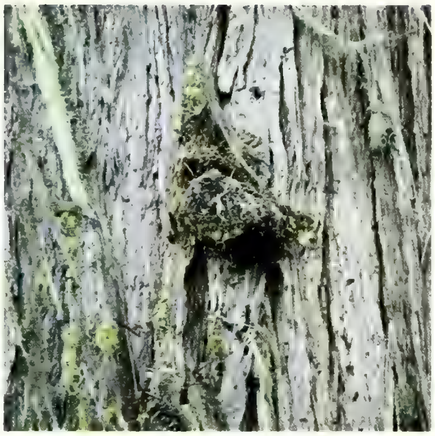


Figure 26. — A shot-hole cup in incense-cedar caused by pencil rot. Note that part of the old conk is still attached.

Early stage: At first, firm and faintly yellowish brown in the pockets. The color deepens slightly with time and the wood becomes soft. This stage extends only a short distance vertically beyond the late stage.

Late stage: Pockets filled with a dark-brown, carbonaceous crumbly mass. A sharp separation occurs between decayed and sound wood.

Mycelium: Small, cobweblike or feltlike masses of white mycelium may occur in pockets.

Key identifying features:

- Conks (when present);
- Shot-hole cups at or below knots; and
- Brown cubical pocket rot.

Cull rules:

For incense-cedar, conk or shot-hole cup indicates a cull tree. Decay is almost always present in trees over 40 inches diameter at breast height and in trees with basal wounds or old, dead limbs.

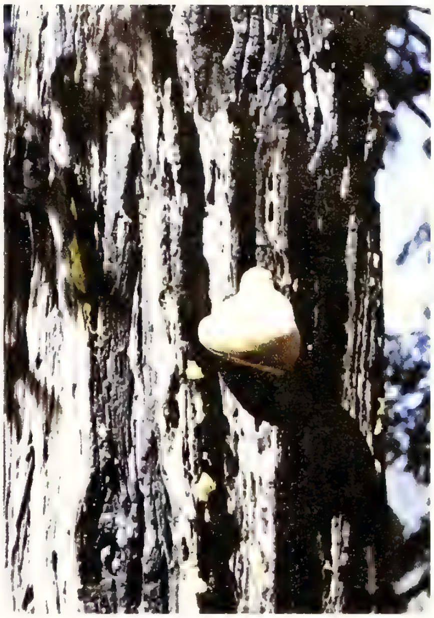


Figure 27. — Sporophore from pencil rot on incense-cedar.

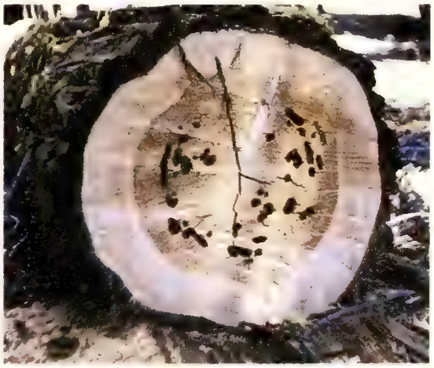


Figure 28. — Cross section of incense-cedar log showing pencil rot decay.

# Injuries Indicating Associated Defect

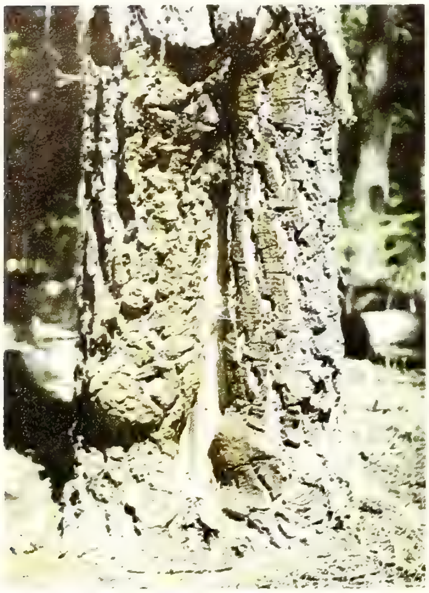


Figure 29. — Old basal injury probably caused by fire.

## Basal Injuries

Basal injuries — open or closed wounds in contact with the ground — are important defect indicators for all tree species. They may be caused by animals, fires, falling trees, or mechanical equipment. Sometimes inconspicuous, they may be easily overlooked. Basal wounds less than 10 years old should be ignored because little or no defect is usually associated with them.

Cull rules:

For white and red fir in southwestern Oregon; deduct 9 feet above the top of the wound.

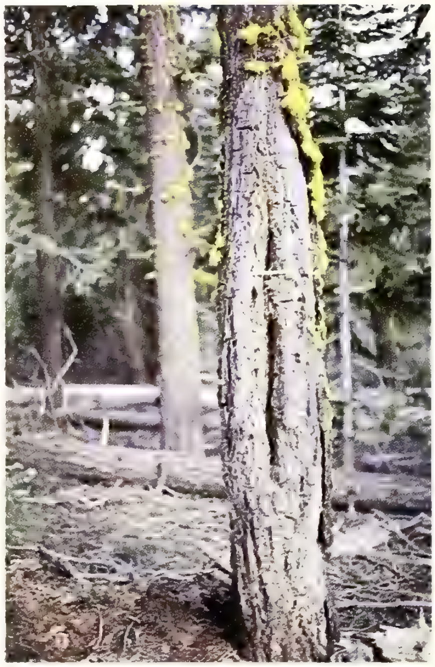


Figure 30. — Trunk injury indicating internal defect.

## Trunk Injuries

Trunk injuries are important indicators for all tree species. They include open or closed wounds more than 1 foot long, more than 10 years old, and located below the merchantable-top diameter, but not in contact with the ground. They are caused by falling trees, logging equipment, lightning, and animals. Small, young wounds are unreliable indicators of decay.

Cull rules:

For white and red fir in southwestern Oregon, deduct 1 foot below the bottom and 2 feet above the top of a wound.

## Frost Cracks

Frost cracks may occur in any species, but they are important defect indicators mainly in true firs and hemlocks. Frost cracks or seams are associated with wounds and wetwood. The cause of wetwood is unknown, but it appears to develop in true firs after wounding. The inrolled callus growth as a wound heals is a weak point in a tree. Freezing of the tree causes a crack to develop from the face of the injury through the bark. In time, the crack may increase longitudinally, and other seams may develop at right angles to the original crack, resulting in a star-shaped pattern. Frost cracks are seldom infection courts for decay fungi. Occasionally, old wounds from which the frost crack originated may have associated decay columns. Because old wounds may no longer be visible, frost cracks are the indicators of defect.

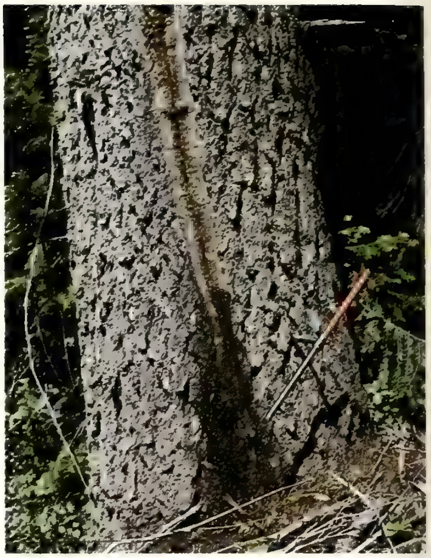


Figure 31. — A frost crack at the base of a white fir.

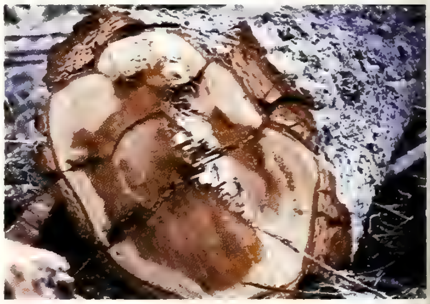


Figure 32. — Cross section at the base of a white fir showing frost cracks, shake, and wetwood.

Cull rules:

No cull rules are available for frost cracks.

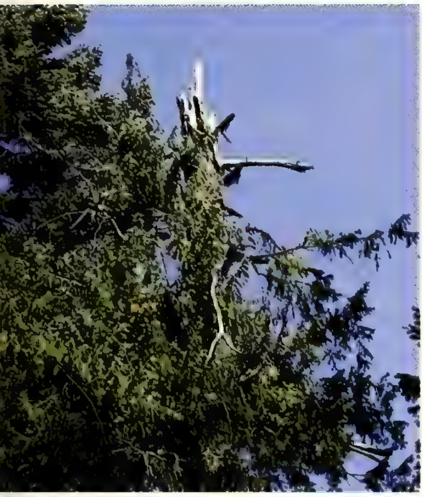
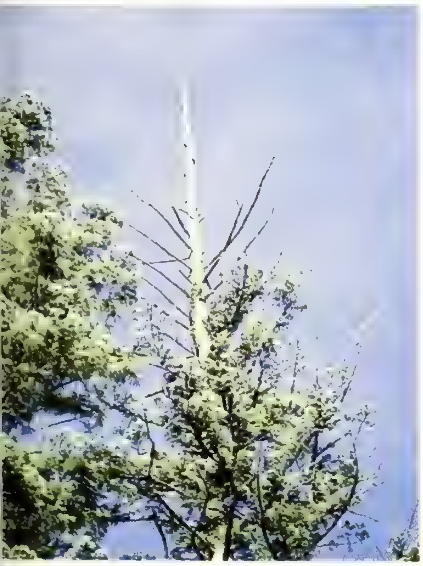


Figure 33. — Broken top in the merchantable portion of a white fir tree.



igure 34. — White fir with a dead top aused by beetle attack.

## Top Injuries

Top injuries include tops broken by vind, ice, or snow and dead tops aused by insects, rust fungi, dwarf nistletoe, and animals. Recent top lamage and damage occuring above he merchantable-diameter limit are not lefect indicators.

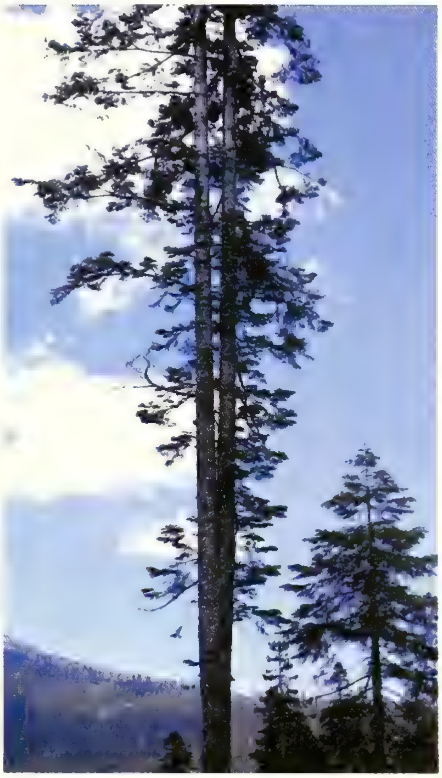


Figure 35. — A forked white fir tree.

## Forks

Forked trees usually result when two or more branches replace a dead or broken leader.

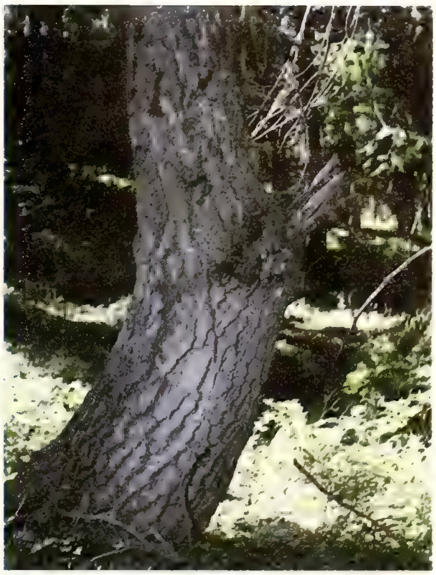


Figure 36. — White fir with a crook caused by death of the leader. Presence of the old, dead top indicates decay.

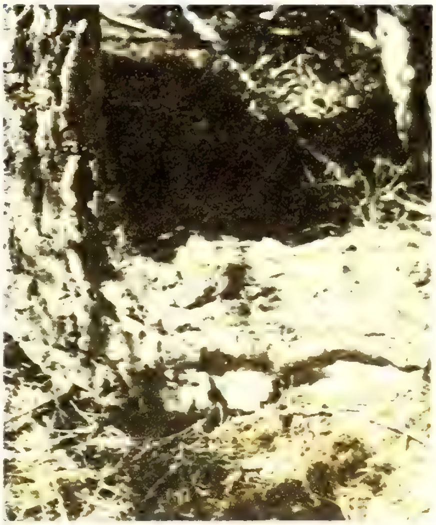


Figure 37. — Crook resulting from bending of young tree by snow or ice. No break occurred, so no decay is present.

## Crooks

Crooks are sudden bends in the merchantable bole of a tree. Crooks may result when young trees bend under ice or snow. This type of crook is free of decay. In older trees, crooks may result from breaks or leader death when a lateral branch assumes dominance and becomes the new tree top. Decay usually is present if the older leader or broken top still remains at the crook.

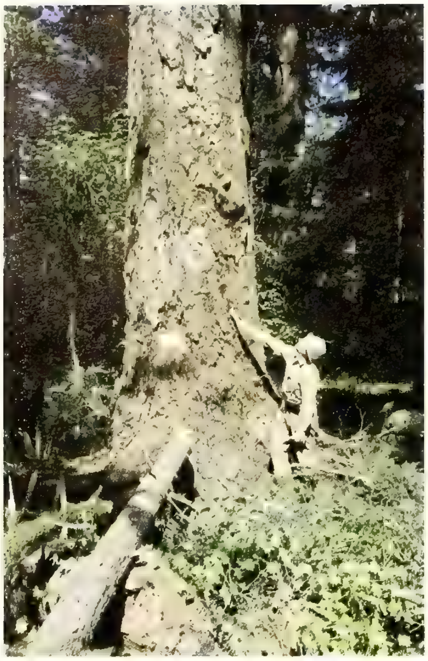


Figure 38. — White fir tree with a swollen butt resulting from healing of an old injury.

## Swollen Butts

Swollen butts are often caused by healing of an old wound or by the reaction of a tree to a root-rot fungus.

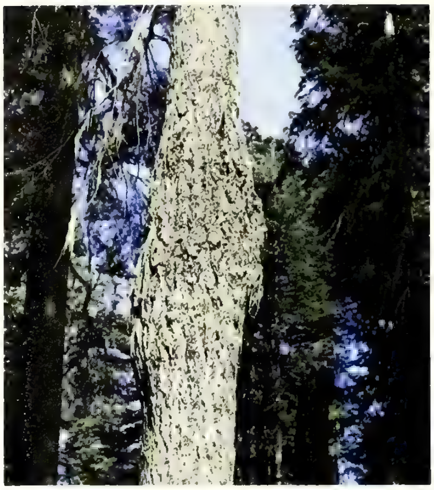


Figure 39. — A dwarf mistletoe bole canker with tight bark; no decay should occur.

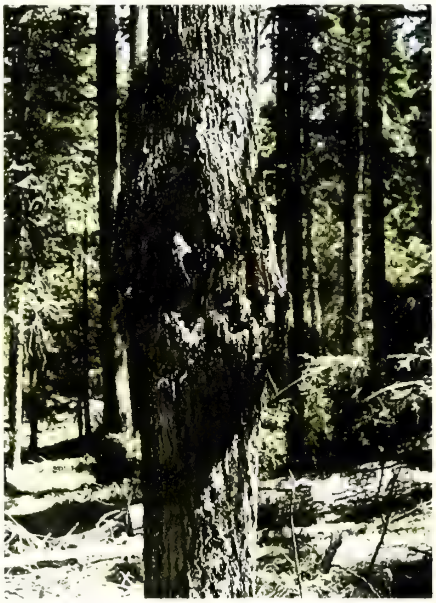


Figure 40. — Open dwarf mistletoe canker on a white fir. Decay may be present, but seldom extends beyond the limits of the swelling.

## Dwarf Mistletoe Cankers

Dwarf mistletoe cankers are large pronounced swellings or cankers produced on branches or boles of host trees by dwarf mistletoes. If the bark is tight, these cankers do not admit decay fungi. When the bark on one of these cankers sloughs off and exposes wood, infection by decay fungi can occur. In white fir, decay generally does not extend beyond the limits of the swelling.

## Additional Sources of Information

Cruisers and scalers in western Oregon may want to search out additional technical information. The following publications will help in making more precise estimates of net volumes in standing trees and logs:

Aho, Paul; Hadfield, Jim. How to estimate defect in white fir in southwest Oregon. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1975. 12 p.

Aho, Paul E.; Roth, Lewis F. Defect estimation for white fir in the Rogue River National Forest. Res. Pap. PNW-240. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1978. 18 p.

Boyce, J.S.; Wagg, J.W.B. Conk root of old-growth Douglas-fir in western Oregon. Bull. 4. Corvallis, OR: Oregon State University, Forest Products Laboratory; 1953. 96 p.

Childs, T.W. Estimating decay in west-side Douglas-fir. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1959. 8 p.

Hunt, J.; Krueger, K.W. Decay associated with thinning wounds in young-growth western hemlock and Douglas-fir. J. For. 60 (5): 336-340; 1962.

Shea, K.R. Decay in logging scars in western hemlock and Sitka spruce. For. Res. Note 25. Centralia, WA: Weyerhaeuser Timber Company; 1960. 13 p.

Wright, E.; Isaac, Leo A. Decay following logging injury to western hemlock, Sitka spruce, and true firs. Tech. Bull. 1148. Washington, DC: U.S. Department of Agriculture; 1956. 34 p.

# Appendix

Table 3 — Scientific names of taxa mentioned in the text

| Common name | Scientific name |
|---|---|
| **Fungi**[1] | |
| Red ring rot | *Phellinus pini* (Thore ex Fr.) A. Ames |
| Red ring rot (var. *cancriformans*) | *Phellinus pini* (Thore ex Fr.) A. Ames var. *cancriformans* Larsen, Lombard, et Aho |
| Red ray rot | *Dichomitus squalens* (Karst.) Reid |
| Red root and butt rot | *Inonotus circinatus* (Fr.) S. C. Teng |
| Rust-red stringy rot | *Echinodontium tinctorium* (Ell. et Ev.) Ell. et Ev. |
| Brown trunk rot | *Fomitopsis officinalis* (Vill. ex Fr.) Bond. et Sing. |
| Red-brown butt rot | *Phaeolus schweinitzii* (Fr.) Pat. |
| Yellow laminated rot | *Phellinus weiri* (Murr.) Gilbn. |
| White spongy rot | *Heterobasidion annosum* (Fr.) Bref. |
| Mottled rot | *Pholiota limonella (Pk.)* Sacc. |
| Yellow pitted rot | *Hericium abietis* (Weir ex Hubert) K. Harrison |
| Brown crumbly rot | *Fomitopsis pinicola* (Swartz ex Fr.) Karst. |
| Brown cubical rot | *Laetiporus sulphureus* (Bull. ex Fr.) Bond. et Sing. |
| Brown top rot | *Fomitopsis cajanderi* (Karst.) Kotl. et Pouz. |
| Pencil rot | *Tyromyces amarus* (Hedgc.) Lowe |
| **Trees** | |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| Fir | |
| California red | *Abies magnifica* A. Murr. |
| Grand | *A. grandis* (Dougl. ex D. Don) Lindl. |
| Noble | *A. procera* Rehd. |
| Pacific silver | *A. amabilis* Dougl. ex Forbes |
| Subalpine | *A. lasiocarpa* (Hook.) Nutt. |
| White | *A. concolor* (Gord. & Glend.) Lindl. ex Hildebr. |
| Hemlock | |
| Mountain | *Tsuga mertensiana* (Bong.) Carr. |
| Western | *T. heterophylla* (Raf.) Sarg. |
| Incense-cedar | *Libocedrus decurrens* Torr. |
| Larch, western | *Larix occidentalis* Nutt. |
| Pine | |
| Lodgepole | *Pinus contorta* Dougl. ex Loud. |
| Ponderosa | *P. ponderosa* Dougl. ex Laws. |
| Sugar | *P. lambertiana* Dougl. |
| Western white | *P. monticola* Dougl. ex D. Don |
| Whitebark | *P. albicaulis* Engelm. |
| Port-Orford-cedar | *Chamaecyparis lawsoniana* (A. Murr.) Parl. |
| Redcedar, western | *Thuja plicata* Donn ex D. Don |
| Spruce | |
| Engelmann | *Picea engelmannii* Parry ex Engelm. |
| Sitka | *P. sitchensis* (Bong.) Carr. |

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[1] Fungi are in order of mention in text.

Aho, Paul E. Indicators of cull in western Oregon conifers. Gen. Tech. Rep. PNW-144. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 17 p.

Descriptions and color photographs of important fungal sporophores (conks), other indicators of cull (wounds), and associated decays in western Oregon conifers are provided to aid timber markers, cruisers, and scalers in identifying them. Cull factors are given for the indicators by tree species.

Keywords: Cull logs, decay (wood), timber cruising, log scaling, coniferae, western Oregon.

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GENERAL TECHNICAL REPORT PNW—145
1982

# WILDLIFE HABITATS IN MANAGED RANGELANDS-- THE GREAT BASIN OF SOUTHEASTERN OREGON

## PRONGHORNS

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FOREST SERVICE U. S. DEPARTMENT OF AGRICULTURE

## ABSTRACT

The sagebrush steppe of the Great Basin in southeastern Oregon is peripheral habitat for pronghorns, but the quality of the habitat can be improved through rangeland management. The relationship between pronghorns and their habitat components—the availability of water, type of forage, barriers that restrict the movement of herds, and the effect of grazing by livestock—are discussed. A worksheet is provided that can be used by range managers to rate the quality of a range as pronghorn habitat. Methods of altering habitat to benefit pronghorns are given.

## THE AUTHORS

ROBERT R. KINDSCHY is a wildlife biologist, U.S. Department of the Interior, Bureau of Land Management, P.O. Box 700, Vale, Oregon 97918. CHARLES SUNDSTROM is a wildlife biologist, U.S. Department of Agriculture, Forest Service, P.O. Box 1628, Juneau, Alaska 99802. JAMES D. YOAKUM is a wildlife biologist, U.S. Department of the Interior, Bureau of Land Management, stationed at Renewable Natural Resources, University of Nevada, Reno, Nevada 89512.

This publication is part of the series **Wildlife Habitats in Managed Rangelands—The Great Basin of Southeastern Oregon**. The purpose of the series is to provide the necessary information on wildlife and its relationship to habitat conditions in managed rangelands in order that the range manager may make fully informed decisions.

The information in this series is specific to the Great Basin of southeastern Oregon and is generally applicable to the shrub-steppe areas of the Western United States. The principles and processes described, however, are generally applicable to all managed rangelands. The purpose of the series is to provide specific information for a particular area but in doing so to develop a process for considering the welfare of wildlife when range management decisions are made.

The series is composed of 14 separate publications designed to form a comprehensive whole. Although each part will be an independent treatment of a specific subject, when combined in sequence, the individual parts will be as chapters in a book.

Individual parts will be printed as they become available. In this way the information will be more quickly available to potential users. This means, however, that the sequence of printing will not be in the same order as the final organization of the separates into a comprehensive whole.

A list of the publications in the series, their current availability, and their final organization is shown on the inside back cover of this publication.

**Wildlife Habitats in Managed Rangelands —The Great Basin of Southeastern Oregon** is a cooperative effort of the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, and United States Department of the Interior, Bureau of Land Management.

## Introduction

Grazing by domestic livestock alters rangeland ecosystems in the Great Basin of southeastern Oregon more than any other humanly controlled activity. Such alteration, coupled with increasing human activities, produces changes that affect pronghorns (*Antilocapra americana*), sometimes called pronghorn antelope. Land managers and land use planners find it increasingly necessary to forecast and display the consequences of management activities on pronghorns.

Primary impacts on pronghorn habitat have resulted from livestock management that alters structural conditions and botanical composition of plant communities. These alterations produce distinct habitat components of differing quality.

This chapter shows the relationship between the pronghorn and its habitat in the sagebrush-grasslands of southeastern Oregon; the principles should also apply to other shrub-dominated rangelands used by pronghorns. The information can be used for both short- and long-range land use planning.

Literature review and consultation with wildlife biologists provided data that formed the framework for relating pronghorns to their habitat requirements. Where data were lacking, the best judgment of the authors prevailed.

## Assumptions

The management tips provided are based on the following information or assumptions:

1. The sagebrush steppe of the Great Basin is peripheral pronghorn habitat (Yoakum 1968) (fig. 1). From reports of early explorers, we conclude that pronghorns were more abundant on the midcontinent short-grass prairies than in the Great Basin (Burroughs 1961, Fremont 1843, Thwaites 1904). Habitat components that limit populations, however, can be manipulated to benefit pronghorns (Yoakum 1978a, 1978b).

2. Pronghorns evolved to be compatible grazers with other native herbivores, especially bison (*Bison bison*)(Yoakum 1978b). Grazing by these native herbivores changed the composition of the vegetation on grassland ranges of North America to favor pronghorns.

Figure 1.—A pronghorn herd on open sagebrush steppe in Lake County, Oregon. (Photograph by James Yoakum.)

3. Forage and drinking water are the primary components of pronghorn habitat. Forage can be improved on ranges in less-than-optimum condition for pronghorns. Water distribution can be improved on some pronghorn rangelands (Yoakum 1978a).

4. Pronghorn ranges contain a variety of plant communities differing in height, composition, and forage production.

5. Pronghorn densities are influenced primarily by habitat conditions (Yoakum 1978a).

6. Favored habitats can be identified by comparing pronghorn densities between habitats (Sundstrom and others 1973).

7. Rangelands with a mixture of grasses, forbs, and shrubs of low structure provide the best pronghorn habitat (Yoakum 1972).

8. Agricultural crops other than alfalfa (*Medicago sativa*) are rarely eaten by pronghorns.

9. Fences, especially those of woven wire, frequently form barriers to pronghorn movement (U.S. Department of the Interior, Bureau of Land Management 1974).

10. The welfare of pronghorns can be enhanced by providing for their needs in range management activities (Yoakum 1978a).

## Habitat Requirements

Pronghorn densities in the Great Basin average less than 0.4 per square kilometer (1.0 mi$^2$) (Yoakum 1968). Variations in density are related to vegetation and water, which are, in turn, related to precipitation and soils (fig. 2). Yoakum (1974) described the following habitat requirements for pronghorn on sagebrush-grasslands.

### ABIOTIC FACTORS

#### Topography

Pronghorns are adapted to low rolling topography with few slopes more than 30 percent in grade. Within such landforms, there are circumstances to which pronghorns adjust by modifying their behavior. Depending on topography, some herds do not move in response to season; some move relatively short distances with change of season and then move even longer distances in response to climatic conditions, such as increasing snow depth.

#### Natural Barriers

Natural barriers to movement include bodies of water, escarpments, mountains, canyons, and areas of tall shrubs or forest, sometimes accounting for isolated, unoccupied habitats that are otherwise suitable (Einarsen 1948).

#### Elevation

Pronghorn ranges occur from sea level to 3 353 meters (11,000 ft) but occurrence at sea level in Mexico and in alpine meadows in Oregon and Wyoming is rare (fig. 3). The largest populations, particularly in the Great Basin, are between elevations of 1 220 and 1 830 meters (4,000-6,000 ft) (Yoakum 1974).

#### Climate

The highest densities, which reflect the best habitats, occur where precipitation averages 25-38 centimeters (10-16 in) per year. Pronghorn in other precipitation zones do reproduce, but they maintain lower densities (Sundstrom and others 1973, Yoakum 1972).

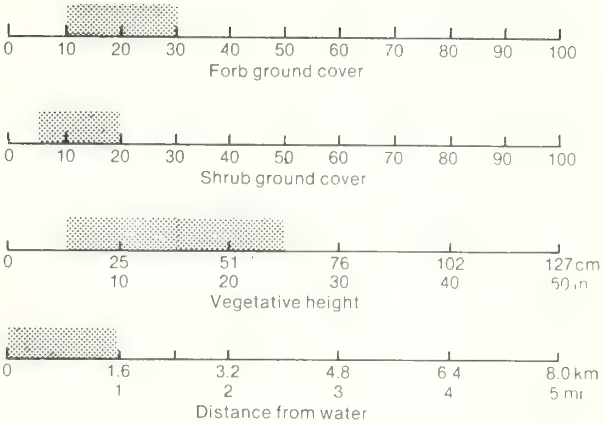

Figure 2.—Components of pronghorn habitat in the sagebrush steppe. Habitat becomes optimum when all components occur together within the bounds marked by bars.

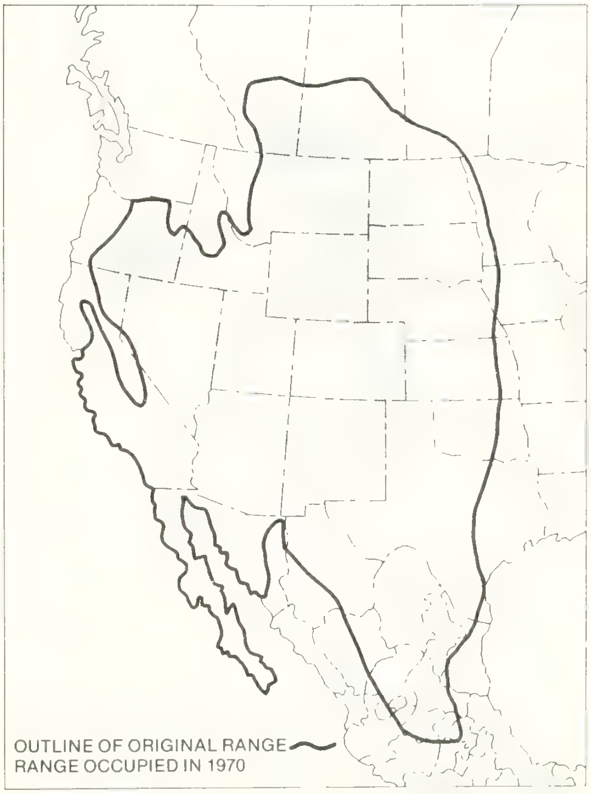

Figure 3.—Distribution range of American pronghorns. the original range denotes only peripheral boundaries because not all areas within it were inhabited. (Adapted from Yoakum 1980).

Whenever Great Basin ranges receive a snow accumulation over 25 to 30 centimeters (10 to 12 in), pronghorns have difficulty obtaining forage. Prolonged periods of such snows are detrimental when one or more of the following occur: low quantity or quality of forage, high winds, and barriers to movement (Bruns 1977, Riddle and Oakley 1973, Sundstrom 1969).

Temperature is usually not a limiting factor. Fawns may die, however, from unseasonable snow or freezing rain (Sundstrom 1968a).

Snow accumulation determines the time and extent of pronghorn movement. The deeper the snow and more rapid the accumulation, the further and faster herds travel toward lower elevations, sometimes traveling as far as 144 kilometers (90 mi) (Mason 1952).

### Soil

The best pronghorn habitats in the Great Basin are found on Aridisols and Mollisols which evolved under a regime of 25-38 centimeters (10-16 in) of precipitation per year.

### Water

Pronghorns require water throughout the year. Springs, rivers, streams, lakes, reservoirs, catchments, and troughs provide drinking water much of the year; snow provides water during winter.

Rangelands providing optimum habitat have drinking water available at intervals less than 8 kilometers (5 mi) (Sundstrom 1968b). Some animals may be found further than 8 kilometers (5 mi) from water, but Sundstrom (1968b) observed that 95 percent of over 12,000 pronghorns were within 4.8 to 6.4 kilometers (3 to 4 mi) of water.

Water consumption by pronghorns varies inversely with the quality and succulence of available forage. When succulent forage is available, 1 liter (0.25 gal U.S.) of water per animal per day is sufficient. When succulence exceeded 75 percent, animals did not drink (Beale and Smith 1970). During dry summers, 4.2-5.7 liters (1.1-1.5 gal U.S.) per day may be needed (Beale 1966).

Drought can reduce the vitality and fertility of pronghorn (Hailey and others 1966, Jones 1949). Pronghorns have killed themselves trying to get through fences to reach water (Baker 1967).[1]

Water quality—particularly total dissolved solids, alkalinity, and pH—is important for pronghorns. The maximum total dissolved solids suitable for ungulate wildlife is 4,500 ppm (McKee and Wolf 1963). Sundstrom (1971) found little use of water with total dissolved solids in excess of 5,000 ppm, and limited use of a source containing 4,620 ppm. Water with pH over 9.25 was not used. Criteria for water quality suitable for livestock and wildlife are given in the tabulation below; the data are interim, however, and should be used only until more precise data are available.[2]

| Criteria | Maximum allowed |
|---|---|
| Total dissolved solids | [3]10 000 mg/liter |
| Free chlorine | 200 mg/liter |
| pH | 7.0-9.2 |
| Manganese | 10 mg/liter |
| Alkalinity (as $CaCo_2$) | 50 mg/liter |
| Chlorides | 1 500 mg/liter |
| Chromium | 5 mg/liter |
| Hardness | 500 mg/liter |

## BIOTIC FACTORS

### Vegetation

Quality and quantity of vegetation are primary influences on pronghorn density. Sagebrush steppe preferred by pronghorns is characterized by Yoakum (1974):

1. Ground cover. Ground cover averages 50 percent living vegetation.
2. Composition. Vegetation averages 40-60 percent grasses, 10-30 percent forbs, and 5-20 percent shrubs.

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[1] Baker, Ted C., Federal Aid Coordinator, Wyoming Game and Fish Commission, Cheyenne. Personal communication; 1967.

[2] U.S. Department of Agriculture, Forest Service, Southwestern Region. Water quality interim guidelines. 1968. Unpublished report on file at USDA Forest Service, Albuquerque, NM.

[3] This figure is probably excessive.

3. Variety. The number of plant species varies from 5 to 10 grasses, 20 to 40 forbs, and 5 to 10 shrubs.
4. Succulence. Succulent plants are preferred forage (Beale and Smith 1970), especially during spring and in some particularly moist summers (fig. 4). Pronghorns move from dry upland ranges to intermittent lake beds and playas to graze succulent vegetation (Good 1977). They also make disproportionate use of recently burned rangelands for foraging, especially in the first growing season after fire. Such areas often provide succulent grass sprouts and an abundance of forbs (Beardahl and Sylvester 1976, Stelfox and Vriend 1977).
5. Range. Open rangelands supporting several plant communities are preferred over monotypic vegetation (Sundstrom and others 1973, Yoakum 1957).
6. Height. Low vegetative structure, averaging 38-61 centimeters (15-24 in) is best. Areas with vegetation taller than 61 centimeters (24 in) are used less; areas with vegetation more than 76 centimeters (30 in) tall are seldom used. Such tall vegetation restricts the pronghorn's ability to see and run—attributes which combine to form the animal's primary defense.

### Animal

Pronghorns historically coexisted in various parts of their extensive range with other ungulates such as bison, elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and bighorn sheep (*Ovis canadensis*) (Einarsen 1948, Nelson 1925, O'Gara 1978, Yoakum 1978b). The bison, especially, grazed dominant grasses, restricting growth of the grass and enhancing production of the forbs and browse favored by pronghorns (Peden 1972).

Coyotes (*Canis latrans*), bobcats (*Lynx rufus*), and golden eagles (*Aquila chrysaetos*) prey on pronghorns, especially fawns (Beale and Smith 1970, 1973; Compton 1958; Hinman 1961; Udy 1953). Bobcat predation on young pronghorns can depress populations on some ranges under certain circumstances (Beale and Smith 1970, 1973). Poor nutrition magnifies the impact of predation (Beale and Smith 1970, Hailey and others 1966). Generally, where habitat is adequate, predation is not a major limiting factor.

Figure 4.—An adult doe eating succulent forbs from a community of grasses. (Photograph by James Yoakum.)

Human disturbance can be particularly harmful on winter ranges and during fawning. Snowmobiles, motorcycles, and low flying aircraft may cause adverse effects.

## Habitat Characteristics

Preferred ranges have shrubs with a mean height of 38 centimeters (15 in) (Yoakum 1974). Low sagebrush (*Artemisia arbuscula*) dominates commonly used summer ranges. The best winter ranges are dominated by shadscale saltbush (*Atriplex confertifolia*), black sagebrush (*Artemisia nova*), and winterfat (*Ceratoides lanata*).

Areas dominated by big sagebrush (*Artemisia tridentata*) are less used, probably because of tall growth of the plant. Alteration of big sagebrush communities by fire or by plowing and chaining to control shrubs increases their acceptance to pronghorns (Yoakum 1978a).

Stands of exotic crested wheatgrass (*Agropyron desertorium* and *A. cristatum*) which include succulent forbs such as dryland alfalfa have become accepted habitats when located near occupied ranges and adequately supplied with water (Heady and Bartolome 1977). When autumn growth of crested wheatgrass and forbs occurs, and the snow cover which follows is light, these rangelands are wintering habitat.

## Management Relationships

The pronghorn population in Canada and the United States increased 1,500 percent from 1924 to 1976 (Yoakum 1978b). Control of hunting and large scale transplanting activities reestablished herds on many historic ranges.

Rangeland management (including vegetation alteration, fence construction, water development, and manipulation of livestock use) influences pronghorn habitat. Management planning that considers pronghorn requirements can minimize adverse effects on pronghorn habitat; some habitat improvement may result. If pronghorn's requirements are ignored, however, severe habitat damage can occur (Wagner 1978).

Nearly all rangelands inhabited by pronghorns are also used by domestic livestock—primarily cattle, sheep, and horses. Utilization of forage in 1975 on the Bureau of Land Management's Vale district in southeastern Oregon is shown in the tabulation below (Heady and Bartolome 1977). Pronghorns consumed less than 1 percent of forage, whereas domestic livestock consumed 83 percent[1].

| **Domestic species** | **Percent forage use** |
|---|---|
| Cattle and horses | 82.3 |
| Sheep | 0.7 |
| Feral horses | 5.8 |
| Total | 88.8 |
| **Wild species** | |
| Pronghorns | 0.9 |
| Mule deer | 10.1 |
| Bighorn sheep | 0.1 |
| Rocky Mountain elk | 0.1 |
| Total | 11.2 |

Insufficient forage for current herbivore populations creates competition for that which is available. Studies of food habits of horses, cattle, domestic sheep, and pronghorns on sagebrush grasslands have shown that horses, cattle, and sheep on sagebrush-grasslands have similar food habits (Olsen and Hansen 1977). Pronghorns do not compete with either horses or cattle when forage and water are abundant. Competition between domestic sheep and pronghorns, however, is more pronounced (Buechner 1950 Hoover and others 1959, Severson and May 1967).

The effect of feral horses on pronghorn habita is largely conjecture. Meeker (1979) studied interactions between pronghorns and feral horses fo one summer in northeastern Nevada and observed no competition at watering sites or interspecific acts of aggression, but evidence of symbiotic relationship, and a dietary overlap o 12.8 percent.

There have been no analyses of the effects o livestock grazing systems on pronghorns for th Great Basin. Most rangelands in southeaster Oregon no longer support yearlong livestoc grazing (Heady and Bartolome 1977). Grazin systems are now based on seasonal needs o livestock while satisfying the physiological requirements of the preferred plant species.

Pronghorns thrive best on ranges with subclimax vegetative composition. These structura and vegetal conditions are created by fire and b the foraging of wild and domestic herbivores The variety of forbs, grasses, and shrubs is ofte higher when the species composition and structural conditions of a plant community are typica of midsuccession.

The quality of rangeland for pronghorns i southeastern Oregon is described by combinations of habitat components identified in fig. 5 An example of how to use the form for ratin pronghorn habitat as summer and winter rang is shown in fig. 6. Where optimum or near optimum vegetative conditions exist, it is best t maintain the plant structure and composition (Yoakum 1980).

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[1] Kindschy, Robert R. The Vale project and wildlife ecology. 1971. Unpublished report on file at the U.S. Department of the Interior, Bureau of Land Management, District Office, Vale, OR.

## WORK SHEET FOR RATING PRONGHORN HABITAT

(sagebrush steppe)

**Step 1.** Circle the most appropriate response in side A of each column (complete cols. 1-7 for rating summer range, cols. 2-4 and 6-7 for winter range). Fill in at bottom corresponding percent of optimum from side B.

| Col. 1* |  | Col. 2 |  | Col. 3 |  | Col. 4 |  | Col. 5* |  | Col. 6 |  | Col. 7 |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Availability of water |  | Vegetative ground cover |  |  |  | Vegetative height |  | Vegetative succulence |  | Fences |  | Slope |  |
| Distance between water in kilometers (miles) | Percent of optimum | Percent shrubs | Percent of optimum | Percent forbs | Percent of optimum | Height, in centimeters (inches) | Percent of optimum | Forbs green | Percent of optimum | Type | Percent of optimum | Percent grade | Percent of optimum |
| A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| 1. 3.2 or less (2 or less) | 100 | 1. 5-20 | 100 | 1. 0-10 | 32 | 1. 25 or less (10 or less) | 90 | 1. All summer | 100 | 1. None | 100 | 1. 0-5 | 100 |
| 2. 3.3-6.4 (2.1-4.0) | 85 | 2. 20-30 | 53 | 2. 10-30 | 100 | 2. 25-50 (10-20) | 100 | 2. To July 15 | 75 | 2. 3-strand barbed wire | 90 | 2. 5-10 | 75 |
| 3. 6.5-9.7 (4.1-6.0) | 57 | 3. 30-40 | 27 | 3. 30-50 | 33 | 3. 50-76 (21-30) | 50 | 3. To July 1 | 50 | 3. 4-strand barbed wire with 41+ cm (16+ in.) clearance | 80 | 3. 10-30 | 50 |
| 4. 9.8-12.9 (6.1-8.0) | 30 | 4. 40-50 | 15 | 4. 50-70 | 17 | 4. 76-102 (31-40) | 10 | 4. To June 15 | 25 | 4. Woven, 81 cm or less (32 in. or less) high | 70 | 4. 30+ | 25 |
| 5. 13.0-16.0 (8.1-10.0) | 12 | 5. 50-70 | 5 | 5. 70-90 | 10 | 5. 102-127 (41-50) | 5 | 5. To June 1 | 10 | 5. Woven, 81+ cm (32+ in.) high | 30 |  |  |
| 6. 16.1+ (10+) | 0 | 6. 70+ | 3 | 6. 90-100 | 5 | 6. 127+ (51+) | 0 |  |  |  |  |  |  |
| Percent of optimum scored: | * |  |  |  |  |  | * |  | * |  |  |  |  |
|  | Col. 1 |  | Col. 2 |  | Col. 3 |  | Col. 4 |  | Col. 5 |  | Col. 6 |  | Col. 7 |

**Step 2.** Calculate habitat rating. Summer range: (a) Sum of the percents of optimum (step 2, cols. 1-7)÷7 = summer habitat rating.
(b) The column with the lowest percent of optimum shows the habitat component most limiting the quality of pronghorn habitat. The lowest percent = primary habitat limiting factor.

Winter range: (a) Sum of the percents of optimum (step 2, cols. 2-4, 6-7)÷5 = winter habitat rating.
(b) The column with the lowest percent of optimum shows the habitat component most limiting the quality of pronghorn habitat. The lowest percent = primary habitat limiting factor.

* Do not complete when rating winter range.

Figure 5.—Worksheet for rating pronghorn habitat (sagebrush steppe).

## WORK SHEET FOR RATING PRONGHORN HABITAT

(sagebrush steppe)

**Step 1.** Circle the most appropriate response in side A of each column (complete cols. 1-7 for rating summer range, cols. 2-4 and 6-7 for winter range). Fill in at bottom corresponding percent of optimum from side B.

| Col. 1* | | Col. 2 | | Col. 3 | | Col. 4 | | Col. 5* | | Col. 6 | | Col. 7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Availability of water | | Vegetative ground cover | | | | Vegetative height | | Vegetative succulence | | Fences | | Slope | |
| Distance between water in kilometers (miles) | Percent of optimum | Percent shrubs | Percent of optimum | Percent forbs | Percent of optimum | Height, in centimeters (inches) | Percent of optimum | Forbs green | Percent of optimum | Type | Percent of optimum | Percent grade | Percent of optimum |
| A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| 1. 3.2 or less<br>(2 or less) | 100 | 1. 5-20 | 100 | 1. 0-10 | 32 | 1. 25 or less<br>(10 or less) | 90 | 1. All summer | 100 | 1. None | 100 | 1. [✓ 0-5] | 100 |
| 2. 3.3-6.4<br>(2.1-4.0) | 85 | 2. [✓ 20-30] | 53 | 2. [✓ 10-30] | 100 | 2. 25-50<br>(10-20) | 100 | 2. To July 15 | 75 | 2. 3-strand barbed wire | 90 | 2. 5-10 | 75 |
| 3. 6.5-9.7<br>(4.1-6.0) | 57 | 3. 30-40 | 27 | 3. 30-50 | 33 | 3. [✓ 50-76<br>(21-30)] | 50 | 3. [✓ To July 1] | 50 | 3. [✓ 4-strand barbed wire with 41+ cm (16+ in.) clearance] | 80 | 3. 10-30 | 50 |
| 4. [✓ 9.8-12.9<br>(6.1-8.0)] | 30 | 4. 40-50 | 15 | 4. 50-70 | 17 | 4. 76-102<br>(31-40) | 10 | 4. To June 15 | 25 | 4. Woven, 81 cm or less (32 in. or less) high | 70 | 4. 30+ | 25 |
| 5. 13.0-16.0<br>(8.1-10.0) | 12 | 5. 50-70 | 5 | 5. 70-90 | 10 | 5. 102-127<br>(41-50) | 5 | 5. To June 1 | 10 | 5. Woven, 81+ cm (32+ in.) high | 30 | | |
| 6. 16.1+<br>(10+) | 0 | 6. 70+ | 3 | 6. 90-100 | 5 | 6. 127+<br>(51+) | 0 | | | | | | |
| Percent of optimum scored: | *<br>30 | | 53 | | 100 | | *<br>50 | | *<br>50 | | 80 | | 100 |
| | Col. 1 | | Col. 2 | | Col. 3 | | Col. 4 | | Col. 5 | | Col. 6 | | Col. 7 |

**Step 2.** Calculate habitat rating. Summer range: (a) Sum of the percents of optimum (step 2, cols. 1-7)÷7 = summer habitat rating.
(b) The column with the lowest percent of optimum shows the habitat component most limiting the quality of pronghorn habitat. The lowest percent = primary habitat limiting factor.

Winter range: (a) Sum of the percents of optimum (step 2, cols. 2-4, 6-7)÷5 = winter habitat rating.
(b) The column with the lowest percent of optimum shows the habitat component most limiting the quality of pronghorn habitat. The lowest percent = primary habitat limiting factor.

* Do not complete when rating winter range.

Summer range:
Total 1→7 = 463 ÷ 7 = 66% of optimum. Water at 30% = primary limiting factor.
Winter range:
Total 2, 3, 4, 6, 7 = 383 ÷ 5 = 77% of optimum. Veg. height at 50% = primary limiting factor.

Figure 6.—Example of completed worksheet.

## Rangeland Manipulation

Manipulating vegetation to increase livestock forage is intensifying in some areas of the Great Basin. An associated activity is modifying the habitat to enhance livestock management and to provide more complete rangeland use; fencing and water developments (fig. 7) are examples.

Figure 7.—Construction of earthern reservoirs provides water for pronghorns in water deficient rangelands of southeastern Oregon. (Photograph by James Yoakum.)

### VEGETATIVE CHANGES

Manipulating vegetation can be either beneficial or detrimental to pronghorns, depending on how it is accomplished (Yoakum 1978b, also see footnote 4). Two basic precautions must be taken: other habitat requirements of pronghorns must be met, and all work should follow the principles of range restoration described by Plummer and others (1968):

1. Changes in plant cover must be justified as biologically desirable.
2. Terrain and soils must be suited to the changes.
3. Precipitation must be adequate to assure establishment and survival of seeded plants (Bleak and others 1965).
4. Competition should not prevent establishment of desired species.
5. Only species and strains of adapted plants should be seeded.
6. Mixtures, rather than single species, should be planted.
7. Sufficiently pure and viable seeds should be planted to increase the probability of success.
8. Seed should be sufficiently covered to enhance sprouting (Basile and Holmgren 1957, Plummer 1943).
9. Planting should be done in the correct season to ensure establishment.
10. The planted area should be adequately protected from livestock, insects, fire, off-road vehicles, etc.

Extensive areas dominated by big sagebrush (where big sagebrush comprises more than 30 percent of the vegetative cover) are marginal pronghorn habitat, especially if the shrubs are taller than 76 centimeters (30 in). Such areas can be treated to decrease the density and height of sagebrush (fig. 8) (Yoakum and others 1980).

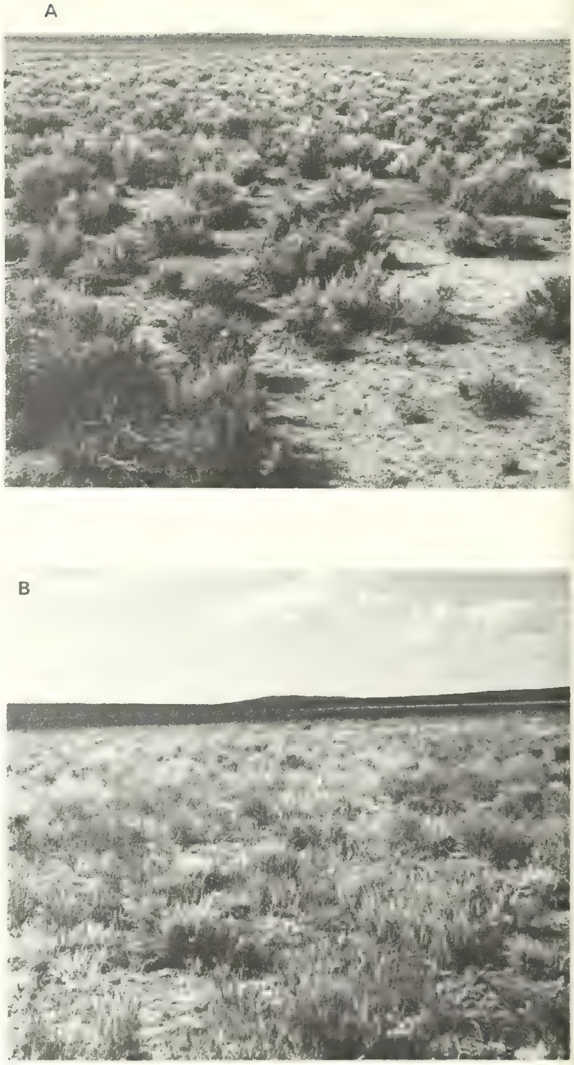

Figure 8.—Results of manipulating vegetation by plowing and seeding: **A**, vegetation before treatment (photographed July 1963); **B**, after seeding (photographed June 1969). The vegetative structure shown in B is more favorable to pronghorns. (Photographs by Robert Kindschy.)

If an area is to be treated, it should probably be no larger than 405 hectares (1,000 acres). The size is based on the assumption that (1) the winter range of pronghorn herds residing in the Great Basin averages 1 215 to 3 025 hectares (3,000 to 5,000 acres) and (2) the treated area should encompass no more than one-third of this winter range. About 5- to 20-percent shrub cover should be retained in the treated area. Because sagebrush and native forbs are important food items (Beale and Smith 1970, Mason 1952, Salwasser 1980, Yoakum 1980), the majority of the natural vegetative communities needed for seasonal use, primarily sagebrush-grasslands, should be retained.

Shrubs are often controlled by mechanical means. Plowing and seeding has been done in many areas of the Great Basin. A brushland plow is often used (fig. 9); this is a disk-type plow developed especially for this purpose. Chaining is another technique widely used. A heavy link ship anchor chain is dragged between two crawler tractors. Chaining does not kill many nonwoody plants or the younger, more flexible shrubs.

Aerial application of herbicide has been a common practice for sagebrush control (Heady and Bartolome 1977). Some applications of 2,4-D have killed nearly all shrubs and perennial forbs. This treatment results in standing dead shrubs that retain their tall structure. Pronghorns usually avoid areas containing such structures for several years (fig. 10).

Historically, fire has been an important influence on the structure of plant communities. Controlled or prescribed fire can control shrubs and is used, on a small scale, as a technique for enhancing habitat. Prescribed burning, properly done, can decrease sagebrush density and enhance opportunities for native grasses and forbs (Beardahl and Sylvester 1976, Lovaas 1976, Page 1975). Fire triggers a series of secondary responses, many of which enhance the habitat for pronghorns. Soil fertility is usually increased. With the canopy removed, soils are warmed by solar heating, promoting earlier vegetative growth in the spring. Plant vigor is increased by removal of senescent shoots and foliage. More forage may become available because some plants become more palatable after burning. Long-term

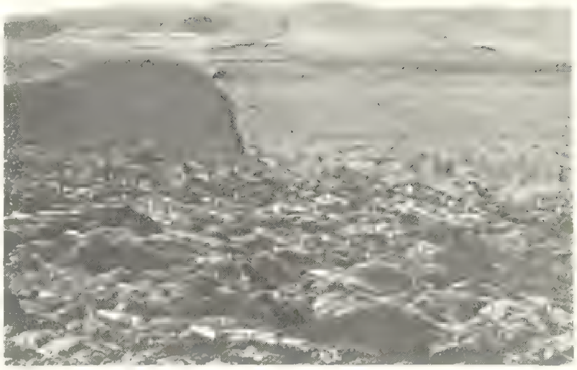

Figure 9.—A brushland plow converts dominated shrublands to communities with comparatively low structure. (Photograph by Robert Kindschy.)

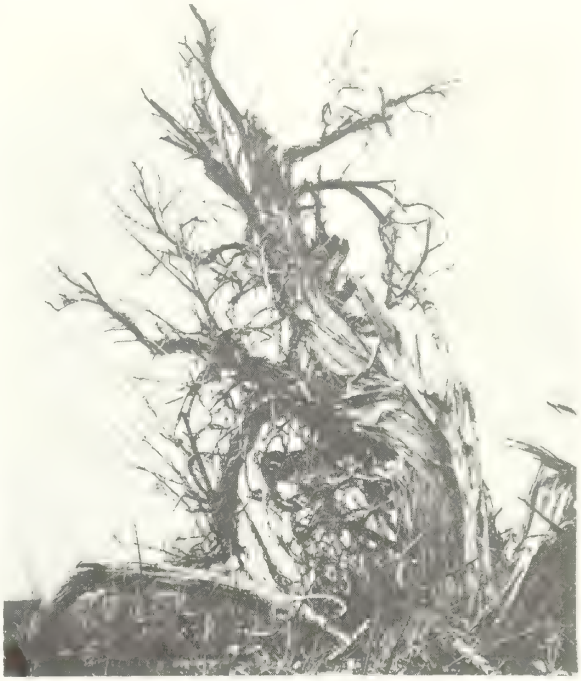

Figure 10.—Big sagebrush killed by chemical application. The skeletons of the sagebrush persist for years and create an unfavorable habitat for pronghorns. (Photograph by Robert Kindschy.)

increases in vegetative growth may be stimulated by timing the burn to favor species with highest yields, by removing competing plants, and by preparing seedbeds for vegetative production.

If a site treated for shrub control has insufficient plants to ensure reproduction, it can be artificially seeded. Such ventures have usually resulted in monocultures of exotic grasses, however, which have limited value to pronghorns other than reducing the height and number of shrubs. Conversely, seeding mixtures have been beneficial to pronghorns, especially when legumes such as dryland alfalfa were included[5] (fig. 11). A useful rule of thumb is to include a minimum of six palatable species each of grasses, forbs, and shrubs (Plummer and others 1968).

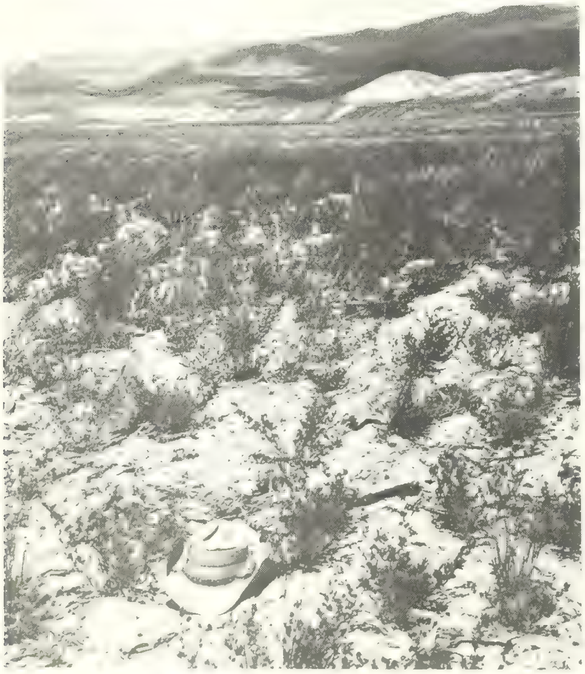

Figure 11.—Using mixtures of forbs and grasses greatly enhances seeded areas as pronghorn habitat. Nomad variety alfalfa and crested wheatgrass were planted in this seeding. (Photograph by Robert Kindschy.)

Pronghorns have used some areas seeded with crested wheatgrass (see footnote 4). Winter use occurs where autumn growth is stimulated by fall rains. Fecal analysis showed that cheatgrass (*Bromus tectorum*), sagebrush, and scarlet globemallow (*Sphaeralcea* sp.) dominated the diet of pronghorns wintering on such areas, crested wheatgrass represented approximately 2 percent.[6]

## WATER DEVELOPMENT

Pronghorns drink from many sources of water, including springs, creeks, rivers, lakes and reservoirs, stock water developments, troughs, and devices for catching precipitation or "guzzlers."

Numerous small reservoirs have been constructed in southeastern Oregon to trap and store precipitation for use by livestock and ungulate wildlife (see fig. 7). Many of these have been constructed on public lands through cooperative funding by State wildlife organizations and Federal land management agencies. In Malheur County, Oregon, 1,037 such reservoirs have been built (Heady and Bartolome 1977).

Another water development valuable to pronghorns is the charco pit or dugout (fig. 12). These earthen pits entrap and store precipitation primarily for livestock and wildlife, but they are readily used by pronghorns, especially during hot late summer months when vegetation is desiccated, and the animals' requirement for water increases.

Wildlife use water from natural springs and seeps. These sources of water are often developed for other uses, such as for livestock, fire suppression, and humans. With minor modifications, such as placing troughs low on the ground, these developments can benefit pronghorns (fig. 13).

Guzzlers can provide water on ranges otherwise lacking in potential sources (June and Higby 1965, Sundstrom 1968b, U.S. Department of the Interior, Bureau of Land Management 1964).

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[5] Kindschy, Robert R. Preliminary report on nomad alfalfa seedings. 1974. Unpublished report on file at the U.S. Department of the Interior, Bureau of Land Management, District Office, Vale, OR.

[6] Spalinger, Don. Notes on the food habits of pronghorn antelope on the Rome seeding, Oregon, during late winter, 1977, with special reference to crested wheatgrass use. 1979. Unpublished report on file at the U.S. Department of the Interior, Bureau of Land Management, Reno, NV.

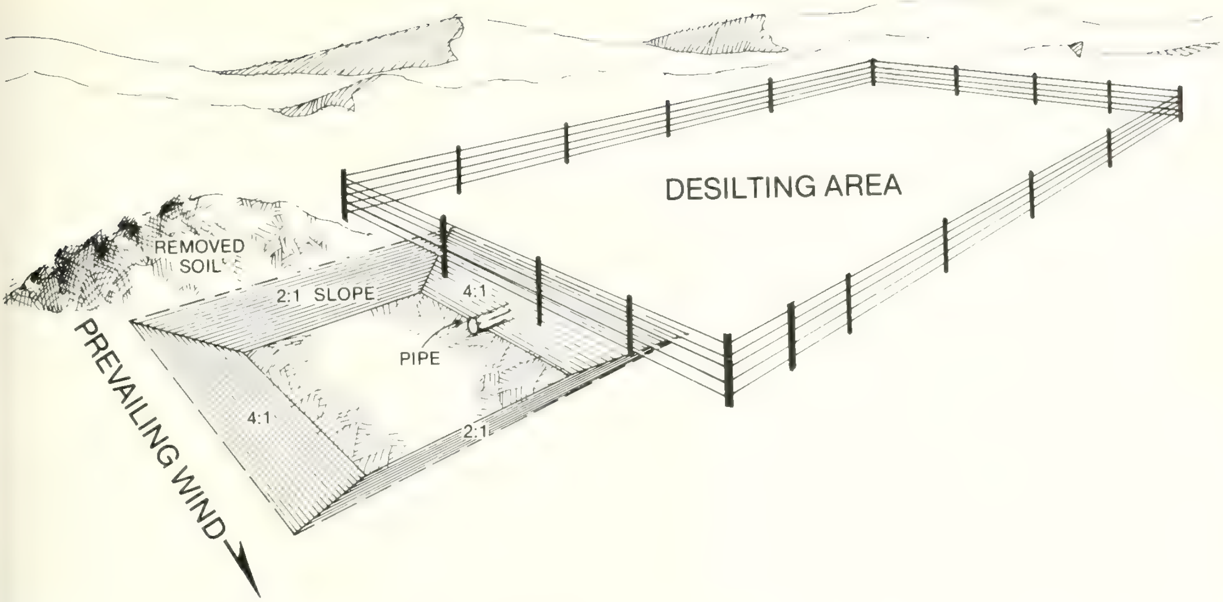

Figure 12.—Charco pit. (Adapted from Yoakum 1980.)

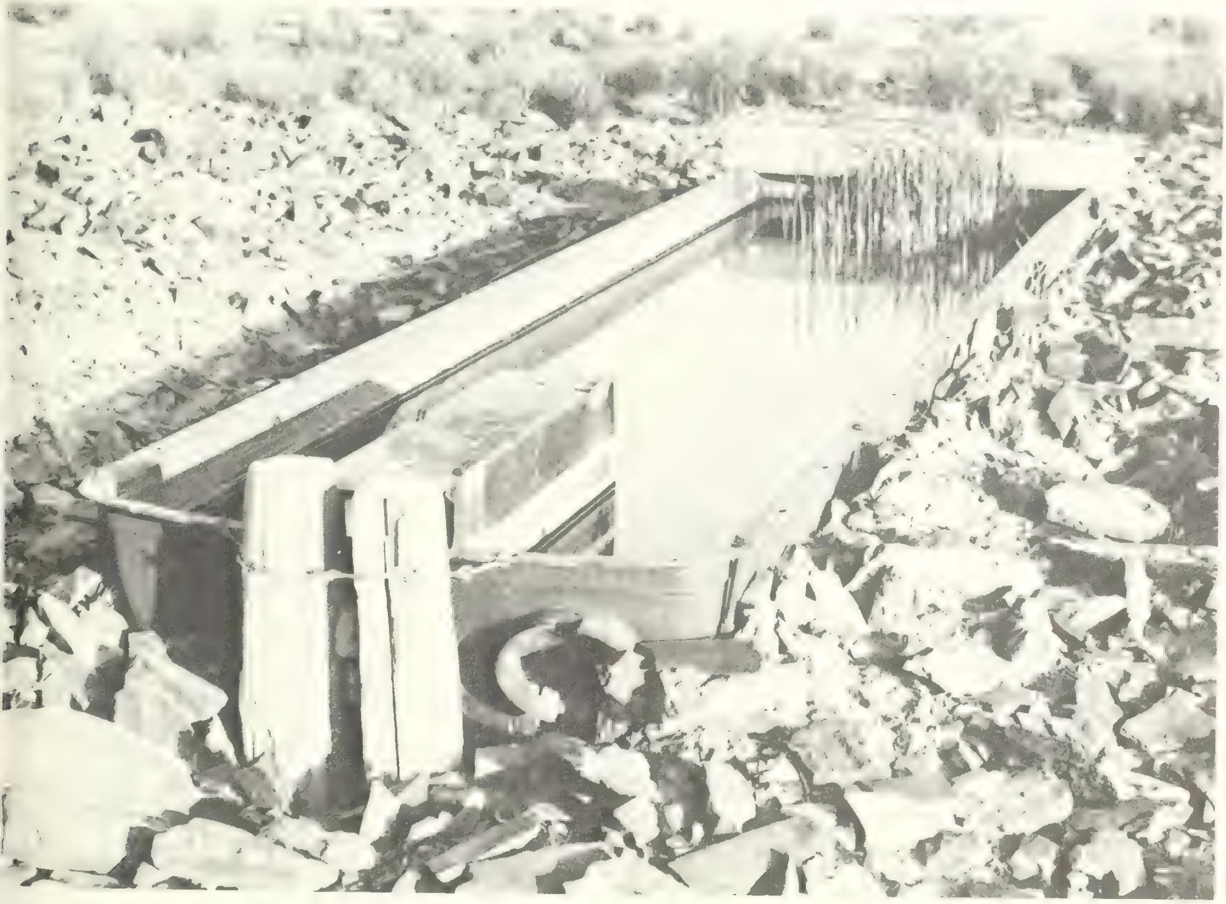

Figure 13.—This trough for livestock and wildlife receives water through a 5-mile pipeline. The trough was installed at ground level to facilitate use and was surrounded by rocks to prevent miring by ungulates. (Photograph by James Yoakum.)

They require little maintenance, are relatively inexpensive, and serve a variety of wildlife. A three-strand barbed wire fence 81 centimeters (32 in) high with a smooth bottom wire at least 41 centimeters (16 in) above the ground can be constructed to exclude cattle and horses. Such construction still allows pronghorns to use the water, but restricts livestock.

### LIVESTOCK FENCING

Fences can restrict the movement of pronghorns, causing changes in herd distribution, deaths, and losses in carrying capacity due to isolation of ranges (Bruns 1977, Hailey and others 1966, Martinka 1967, Oakley 1973, Sundstrom 1970).

The following specifications, resulting from intensive studies, are recommended for fence construction in areas used by pronghorns (Mapston 1972; Spillet and others 1967; U.S. Department of the Interior, Bureau of Land Management 1974, 1975; Zobell 1968):

1. The use of woven or net-wire fences should be minimized.
2. Areas encircled by the types of fences that hinder pronghorn movement should be large enough to include their yearlong habitat needs.
3. Pathways and migration routes of pronghorns should have low fences, lay-down panels, pass structures, or adjustable spacing of the wire (Yoakum 1980).
4. Barbed wire fences with no more than three strands can be negotiated by pronghorns. The bottom wire should be smooth (no barbs) and be at least 41 centimeters (16 in) above the ground. Remaining wires shoud be spaced at 25-centimeter (10-inch) intervals. The total height of the fence should not exceed 91 centimeters (36 in), and there should be no stays between posts (fig. 14).

New fences should have white rag flagging tied to the top wire between each post. Pronghorns will, to some extent, adapt to the fence by the time the flagging deteriorates.

Although pronghorns normally pass under or through fences, some learn to jump fences up to 81 centimeters (32 in) high. Woven wire fences are sometimes considered necessary to control domestic sheep. Of the designs tested, the least detrimental to pronghorn passage were (1) a span of net or woven wire 81 centimeters (32 in) high without single strand(s) of wire above, or (2) a span 66 centimeters (26 in) high with one barbed wire 10 centimeters (4 in) above the net wire (Spillet 1965).

## Management Tips

Where pronghorns are selected as a featured species for management and their welfare is an objective of management, the limiting factor(s) for each range should be identified and appropriately altered if habitat is to be improved (see figs. 4 and 5). Following are suggestions, including guidelines from the 1978 pronghorn antelope workshop (Autenrieth 1978):

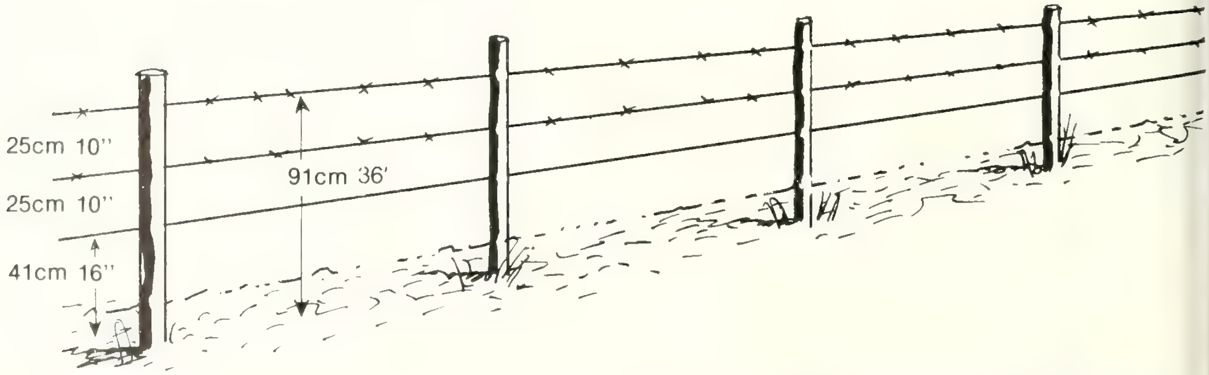

Figure 14.—Specifications for livestock fences constructed of barbed wire on pronghorn ranges (U.S Department of the Interior, Bureau of Land Management 1975).

## HABITAT

1. Where precipitation is less than 15 centimeters (6 in) per year, the vegetation should not be manipulated.

2. The best ranges have at least 50-percent ground cover and the vegetative structure is no taller than 38-61 centimeters (15-24 in).

3. A vegetative composition that averages 40-60 percent grasses, 10-30 percent forbs, and 5-20 percent shrubs is best.

4. High diversity in vegetation is preferable: 5-10 grass species, 20-40 forb species, and 5-10 shrubs.

5. Where plants are seeded, it is important to select species that will ensure succulence into late summer. Dryland alfalfa is an example. Maintenance, improvement, or creation of wet meadows is likewise important.

6. Livestock grazing systems designed to ensure sufficient seasonal forage can also benefit pronghorn. For example, the number of livestock on spring pronghorn ranges can be adjusted to assure growth of vernal forbs, and sheep can be restricted from pronghorn fawning areas for 15 days before and after the peak fawning season (May 15 to June 15). Adequate forage on winter ranges is particularly important; inadequate forage frequently limits the size of pronghorn herds.

7. Pronghorns require 0.9 kilogram (2 lbs) of air-dried, preferred forage per animal per day (Severson and others 1968). This should be consciously provided through management.

## WATER

1. Water sources on pronghorn summer ranges are most beneficial when no more than 4.8 kilometers (3 mi) apart and when they are designed and managed for pronghorns, even when livestock are moved to other pastures. In addition, on livestock summer ranges that serve as critical pronghorn winter ranges, some water sources can be restricted from livestock use. The restriction can help prevent overuse of surrounding vegetation by livestock.

2. Availability of water is particularly important on summer ranges from June through October, when each adult pronghorn requires 1.0 liter (1/4 gal U.S.) per day.

3. Water is most palatable to pronghorn when the pH is less than 9.25 and the total dissolved solids are less then 5,000 ppm.

## FENCING

1. Pronghorns fare best when fences for controlling livestock movement have no woven wire and are built in such a way to allow pronghorns to pass.

2. Barbed wire fences with smooth bottom wires at least 41-46 centimeters (16-18 in) above the ground, no stays, and a top wire no higher than 81 centimeters (32 in) allow pronghorns to pass.

3. White-topped steel fenceposts will increase the visibility of the fence.

4. White cloth strips tied to the top wire between posts of a new fence will also increase the visibility of the fence and will allow pronghorns to become used to its location.

5. Lay-down panels or "antelope passes" can be constructed at strategic points to allow pronghorns to move between areas. In addition, gates can be left open when livestock are removed from fenced pastures.

## HARASSMENT

Human activities disturb pronghorns. Controlling the use of motor vehicles, particularly off-road vehicles, on summer ranges during fawning season (May 15 to June 15) and on winter ranges when herds are concentrated (December 1 to March 15) will minimize disturbance.

## GRAZING

Domestic sheep are generally more competitive with pronghorns for preferred forage than are cattle and horses. In addition, the net wire fences commonly used to contain sheep often limit the movement of pronghorns. Pronghorns usually fare better when grazing with horses and cattle than when grazing with sheep.

## Summary

The old adage that "good" range management is "good" for wildlife was probably never true and is no longer acceptable (Thomas 1979), certainly not for pronghorns. Improvements in pronghorn habitat, to date, have largely been a byproduct of management activities to improve conditions for livestock. But pressure for increased livestock production is accompanied by a growing public concern for wildlife. Pronghorns can benefit from range management activities only if their welfare is planned in advance and their habitat requirements are no longer left to chance.

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WILDLIFE HABITATS IN MANAGED RANGELANDS — THE
GREAT BASIN OF SOUTHEASTERN OREGON

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# Evaluating Projects for Improving Fish and Wildlife Habitat on National Forests

Fred H. Everest and Daniel R. Talhelm

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## Authors

FRED H. EVEREST is a research fisheries biologist, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331. DANIEL R. TALHELM is a fisheries and wildlife economist, Michigan State University, East Lansing, Michigan 48104.

## Common and Scientific Names

| Common name | Scientific name |
|---|---|
| Coho salmon | *Oncorhynchus kisutch* (Walbaum) |
| Chinook salmon | *Oncorhynchus tshawytscha* (Walbaum) |
| Cutthroat trout | *Salmo clarki* Richardson |
| Rainbow (steelhead) trout | *Salmo gairdneri* Richardson |

## Abstract

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Recent legislation (P.L. 93-452; P.L. 94-588) has emphasized improvement of fish and wildlife habitat on lands of the National Forest System. A sequential procedure has been developed for screening potential projects to identify those producing the greatest fishery benefits. The procedure — which ncludes program planning, project planning, and intensive benefit/cost analysis — has nationwide application for both fish and wildlife projects Fisheries and wildlife values are difficult to assess and available estimates are far from ideal, but better estimates are gradually becoming available.

Keywords: Habitat improvement, wildlife habitat, cost/benefit evaluation, program planning, salmonids.

## Contents

1 **Introduction**
2 **Benefit/Cost Concepts**
3 **Program Planning**
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## Introduction

In the 1970's, Congress formally recognized the potential value of improving fish and wildlife habitat on the National Forests by requiring comprehensive planning for fish and wildlife on National Forest System lands (Sikes Act, P.L. 93-452, as extended in 1974). USDA Forest Service budgets for habitat improvement have grown steadily in recent years, and the National Forest Management Act of 1976 (P.L. 94-588) provided the option to use Knutson-Vandenberg funds for habitat rehabilitation and enhancement within designated timber sales. These recent actions have enabled forest managers to initiate a positive program to improve fish and wildlife habitat on the National Forests. But because more potential projects exist than can be completed annually with existing funds, projects that provide the greatest benefits must be selected.

Biologists, economists, and others who participate in the planning and selection process have difficulty comparing project alternatives objectively because the range of potential projects is so great, and little information has been available for estimating expected benefits from projects. Thus standard, objective evaluation tools, such as benefit/cost analyses, have been difficult to use. Ideally, projects can be compared by evaluating the benefits and costs of each alternative. Project benefits can be defined as the degree to which people are better off with the project than without it. This can be estimated in terms of the aggregate willingness of people to pay to have the project rather than to go without.

# Benefit/Cost Concepts

Unfortunately, this information is not available for most fish and wildlife projects because of the lack of conventional markets for recreational use of fish and wildlife. How willing recreational users are to pay for changes in the fish and wildlife resource is not generally known. Most economic studies of recreation are not directly usable either because they evaluate something other than willingness to pay for resource use (such as studies of expenditure patterns), or because they estimate willingness to pay for broad, drastic choices (such as the willingness of anglers to pay for a State's entire coastal anadromous fishery rather than not have it at all, called the "all-or-none" value), rather than willingness to pay for the much smaller effects of specific projects (Talhelm 1980). All-or-none values can differ greatly from project values. Even the value of fisheries resources to the commercial fisheries sector is difficult to estimate. The commercial fisheries' net willingness to pay for improved fishing would be the market value of the additional fish minus additional costs of harvesting and bringing them to market. The market values may be well known, but the costs are not.

Biologists working in the National Forests usually cannot obtain the proper kinds of value information for each alternative, so they must use shortcut procedures and rules of thumb instead. Our objective is to explain and illustrate some useful procedures for planning fish and wildlife programs and projects for National Forests, and for estimating fish and wildlife values—and to contrast all of these with ideal procedures. Procedures are illustrated with a specific example from the Siskiyou National Forest of southwest Oregon. Before we discuss procedures for program and project planning, however, we first present a brief explanation of benefit/cost concepts (adapted from Francis et al. 1979).

When we ask whether the benefits of rehabilitation will exceed the costs, what are we really asking? One answer is that we are asking whether, over the long run, the gains outweigh the costs. If so, theoretically, the gainers could pay the capital and labor costs and compensate any losers so that in the end, none would feel worse off and at least one group would feel better off. This is the same question you implicitly ask yourself when you decide whether you should purchase any product in the market. If you voluntarily purchase something at a given price, you do so because you think you will be better off with the product, and your payment will have compensated the producers. Both you and the producers have volunteered to buy and sell, so you both must have decided the exchange was in your best interests. The main difference in rehabilitation is that the beneficiaries of public decisions may not be the only ones who pay the costs, and the losers are not always compensated.

Compensation is considered adequate for our purposes when everyone feels at least no worse off, after the change has been produced and compensation has been paid. Adequate compensation, then, is the minimum required to make people who have given up something feel as well off as before. In other words, it is their willingness to accept compensation. In analyzing public decisions, economists look at two values: the benefits, measured in terms of the maximum the public would be willing to pay; and the costs, measured in terms of the minimum the public would be willing to accept as compensation. These values are easily measured in an ongoing market where payments are offered and accepted, but where is the market for rehabilitation projects?

If long-run benefits exceed long-run costs, the project is probably a good choice for society unless better choices are available because the social gains outweigh the social costs—a gain in aggregate welfare for society. This is because if compensation were paid no one would be worse off and at least some members of society would be better off. These gains and losses can also be assessed in ways other than through economic analysis (such as through political processes or Delphic methods), and sometimes that is necessary if the benefits, costs, or both cannot be accurately estimated. Accurate economic benefit/cost analysis, however, has the advantage of providing confidence that we have arrived at the best decision.

Although benefit/cost analyses assess social choices in an important sense, they do so only in special, confined ways. Certain social values or considerations are usually not addressed in benefit/cost analyses. Those considerations are social equity; human rights or other ethical judgments; economic impacts; and major shifts in social policy.

Social equity in the economic sense is usually thought of as the distribution o income or wealth among members of our society. Because the benefits and costs of projects are measured in term of willingness to pay or to accept compensation, both of which depend upon the current distribution of wealth, all benefit/costs analyses depend to some extent on current distribution of income. The results might differ if income were distributed differently. In fact, whether or not gainers actually pay losers will have some effect on income distribution, so even this could affect the results of a benefit/cost analysis. In addition, if the existing distribution of income in society were considered unfair, then the results of any benefit/cost analysis might also be considered unfair. The effects of income distribution are ignored in benefit/cost analyses. But political and administrative decisionmaking processes often consider, in one form or another, the equity effects of incom distribution.

Human rights and other ethical judgments are also usually ignored in benefit/cost analyses. Obviously these are based on human biases, but benefit/cost analyses do not attempt to distinguish good from bad ethics. Political judgments may, however, and those judgments can override benefit/cost analyses.

To economists, economic impacts are measures of the transfer of income, employment, or both from one region to another or from one sector of the economy to another as a result of some change in the economy. You often hear about dollars spent by recreationists at motels, restaurants, and gas stations, or that commercial fisheries not only employ the fishers themselves but also the processors and perhaps local restaurant personnel. Secondary impacts are usually not relevant in benefit/cost analyses because they are not direct measures of benefits or costs, but of the location of economic activity. The only aspects of economic impacts that should be included in benefit/cost analyses are the positive or negative values of alleviating or causing unemployment of capital, labor, or both, and the value of progress toward or away from any social goal of transferring income and employment from one region or economic sector to another. Communities and regions are often concerned with economic impacts because they greatly influence patterns of local growth and community integrity. These considerations are more likely to form part of a political judgment than a benefit/cost analysis because economists have great difficulty measuring the values represented by such concerns.

Finally, the "macro" judgments of any society are usually considered beyond the useful scope of benefit/cost analysis. For example, the decision to open western North America to homesteading and the decision to put a man on the moon by 1970 both represent deliberate political choices resulting in major changes for society. These kinds of decisions lead to changes that are uncertain or even totally unanticipated at the outset. The decisions are made only because of a strong conviction that the ensuing benefits will more than offset the costs. A traditional, detailed benefit/cost analysis is neither possible nor would it increase public confidence in the merits of this kind of decision. Any major redirection of society or its economy will in itself change the values we rely upon to estimate dollar benefits and costs, thereby reducing the reliability of the analysis.

Social equity and human rights must be considered separately and weighed against the benefit/cost analysis of any project. A logical approach would be to complete the benefit/cost analysis and then to follow any explicit Forest Service guidelines, or if these are unavailable, to ask an advisory committee to rerank projects on the basis of human values. Public hearings could be held or elected representatives might rerank the projects. Obviously, any of these processes might result in socially worse rankings than the original ones, or the costs of the reranking process may be greater than the benefit received. That social equity and human rights values would significantly alter many fish and wildlife project analyses for National Forest projects is unlikely, however.

## Program Planning

Program planning—the initial step—is a broad evaluation of the entire range of potential projects, with the objectives of identifying the kinds of projects worthy of more detailed evaluation in the project-planning stage, and understanding how these projects relate to each other and to other goals and objectives of the Forest and of related agencies. Ideally, the benefits and costs of each possible project would be evaluated. In this context, program planning can be viewed as a generalized benefit/cost evaluation, accepting or rejecting whole, broad categories of possible projects to permit the planner to concentrate on the most likely projects.

This process is often not even recognized as a form of benefit/cost analysis. Planners often speak of identifying needs and types of projects that would meet those needs. On closer examination, however, needs are simply results likely to be highly beneficial. An area with few angling opportunities relative to the potential angling effort is spoken of as having a deficit of angler days or a need of so many angler days. In other words, the benefits of providing for additional angler days there are likely to be great. Quantifying potential benefits would be a much more precise way of understanding need, but shortcut procedures are more expedient at this stage.

### Identifying Needs

Program development must be responsive to local and national needs for recreation, commercial fishing, or enhancement of habitat for threatened or endangered species. Statewide comprehensive plans, State fish and wildlife plans, and the Endangered Species Act of 1973 (P.L. 93-205) are examples of documents that can be used to identify needs for habitat improvement.

**Table 1 — Deficits in catch of anadromous and resident salmonids in southwest Oregon in 1980, and Siskiyou National Forest's potential to eliminate deficits by enhancing habitat**

| Salmonids | Deficit | | Enhancement potential |
|---|---|---|---|
| | Number of fish caught | Activity-days | |
| | ANADROMOUS | | |
| Spring chinook | 400 | 3,000 | Low |
| Fall chinook | 1,000 | 6,000 | High |
| Coho | 1,000 | 1,000 | Medium |
| Summer steelhead | 400 | 3,000 | Low |
| Winter steelhead | 1,000 | 5,000 | High |
| Cutthroat | 300 | 300 | High |
| | RESIDENT | | |
| Trout in streams | 18,000 | 7,000 | Low |
| Trout in lakes | 74,000 | 30,000 | Low |

An example from southwest Oregon illustrates how these needs are identified. Data in the Oregon Statewide Comprehensive Plan (USDA Forest Service 1976) indicated that a deficit in supply of most anadromous and resident salmonids occurred within the State in 1980. The most serious deficits in southwest Oregon were associated with fisheries for fall chinook salmon, coho salmon, winter steelhead, and resident trout in lakes and streams (table 1).

Habitat improvement on the Siskiyou National Forest could eliminate a portion of the deficit in recreational angling. The Forest contains portions of 11 river basins producing anadromous salmon and trout; it supports one of the largest anadromous fisheries in the National Forest System. Angling for resident trout in the Siskiyou is minor. The Forest's streams support few fishable populations of resident trout, and only a few small fishing lakes are present. The potential for development or improvement of additional lakes is not great. Clearly, the highest potential for improving fish habitat lies in segments of streams used by anadromous salmonids. Consequently, efforts to improve fish habitat on the Siskiyou were directed first toward eliminating deficits in supply of anadromous salmonids. Improvement of habitat for fall chinook and winter steelhead offers the greatest potential for reduction of deficits.

The capacity of forests in western Oregon to produce resident and anadromous salmonids, as well as other species, varies; regional coordination of proposed projects would in some general way compare expected levels of benefits and costs between Forests. Intraregional coordination of Forest Service projects, and coordination with States and other Federal agencies, should avoid duplication of effort and potential conflicts, as well as direct more funding into the most cost/beneficial areas.

## Selecting Projects to Meet Needs

What types of habitat could be improved on the Siskiyou to meet deficits in populations of fall chinook salmon and winter steelhead? To answer this question, factors limiting populations of these species were explored, for both marine and freshwater phases in their life histories. Successful coastwide programs for enhancing hatcheries suggested that the marine environment was not currently limiting any populations of anadromous salmonids produced in southwest Oregon. In fresh water, either spawning or rearing habitat could have been limiting; however, with rare exception, streams on the Siskiyou contained spawning gravels in excess of requirements for seeding the available rearing areas. Increasing spawning gravels would have little or no benefit. Rearing habitat is the limiting factor in most streams on the Forest, primarily because of low streamflows associated with droughty conditions common to southwest Oregon in summer.

What types of projects could most efficiently enhance or expand available rearing areas? Only a few options are available to compensate for shortages of water; a promising one was to allow anadromous salmonids access to unoccupied habitat. Several natural barriers on streams of the Siskiyou block upstream migrants from suitable spawning and rearing habitat. Removing or laddering such barriers could increase production of fall chinook and winter steelhead, and deserved careful study. Program planning started with this type of project but was ultimately expanded to consider all types of projects that could enhance production of anadromous salmonids.

## Selecting Geographic Areas for Projects

Other considerations being equal, projects should be located in river basins that have the highest potential to produce additional fish. On the Siskiyou National Forest, the Rogue, Illinois, Chetco, and Elk Rivers probably best fit this category. Projects in those rivers are probably most cost effective—they will probably produce the greatest immediate results (numbers of fish) from funds invested. Potential projects in less productive watersheds, however, should also be considered because the benefits in some, more costly areas could be proportionally much greater than in lower cost areas. Existing data should be compiled for each potential project in which barrier removal or laddering, for example, would benefit anadromous salmonids.

**Table 2 — Fish species blocked from upstream access by barriers on Siskiyou National Forest streams**

| Watershed and streams | Anadromous salmonids | | | | |
|---|---|---|---|---|---|
| | Fall chinook | Coho | Summer steelhead | Winter steelhead | Cutthroat |
| | | CHETCO | | | |
| Emily | X | X | | X | X |
| Eagle | | | | | X |
| | | COQUILLE | | | |
| South Fork | | X | | X | |
| Elk | | X | | X | |
| | | ELK | | | |
| Anvil | | X | X | | X |
| Rock | | X | X | | X |
| | | ILLINOIS | | | |
| Briggs | | | | X | |
| Cave | | | | | X |
| Collier | X | | | X | X |
| Grayback | | | | X | |
| Indigo | X | | | X | X |
| Lawson | X | | | X | X |
| Silver | X | | | X | X |
| Sucker | | | | X | |
| | | ROGUE | | | |
| Burned Timber | | | X | X | |
| Shasta Costa | X | X | | X | X |
| Stair | | | | | X |
| | | SIXES | | | |
| Dry | X | X | | X | X |

## Selecting Project Sites

Inventory data currently available on the Siskiyou list 18 barriers that are restricting upstream access for anadromous salmonids (table 2), but the inventory is incomplete. Additional stream surveys will increase the number of potential projects. Potential sites should be jointly selected by State and Federal agencies.

## General Evaluation of Potential Projects

Each site identified is a potential project, but intrinsic or extrinsic factors might preclude its development. Criteria for eliminating projects might include, at least: the species of fish that will benefit; legal constraints; and administrative restrictions on certain projects or geographic areas. This amounts to a simple form of project evaluation that will probably reduce the number of potential projects. Projects not eliminated should be subjected to project planning to determine their priority for development.

## Project Planning

The next step in development of a habitat-improvement program is project planning, in which all barriers listed in table 2 would be subjected to an intense analysis of benefits and costs. A natural falls on Shasta Costa Creek in the Rogue Basin illustrates the process of project planning. All barriers in table 2 should be subjected to the same kind of analysis, and ultimately, so should all other potential projects. The focal point of project planning is a feasibility study, which as a minimum includes: an environmental assessment; an engineering investigation; a preliminary design; and a benefit/cost analysis. Four basic areas of project feasibility will be analyzed during the project-planning process — physical, biological, economic, and social.

The economic analysis is the heart of the feasibility study. All costs associated with the project (planning, construction, operation, and maintenance) must be accurately defined over the expected life of the project. Costs can often be identified precisely, but benefits must also be realistically analyzed in detail — and this is perhaps the most difficult aspect of benefit/cost analysis for projects to improve fish and wildlife habitat.

The first step is estimating increased biological production. How many adult fall chinook salmon or winter steelhead will the Shasta Costa project produce? The question is best answered by relating production per unit area below the barrier to comparable spawning and rearing area above the barrier. Laddering will open about 4.76 km of good spawning and rearing habitat for winter steelhead and cutthroat trout, and about 1.60 km for chinook and coho. Stream surveys and redd counts on Shasta Costa Creek indicate that about 43 pairs of steelhead, 13 pairs of fall chinook, 3 pairs of coho, and 12 pairs of cutthroat spawn annually per kilometer of accessible stream. Applying these data to potentially available habitat above the falls, an increased annual escapement of 200 pairs of steelhead, 20 pairs of chinook, 5 pairs of coho, and 60 pairs of cutthroat could be expected to result from laddering. Expected catch of salmon is five times escapement, and expected catch of steelhead and cutthroat from Shasta Costa Creek are 25 and 20 percent of escapement, respectively. No benefits would be realized the first 3 years of the project, and only half the potential annual benefits would be realized during the second 3-year period because of the cyclic life-history patterns of these species. These estimates appear conservative, but we think they are realistic based on observed use of downstream waters.

How can the benefits of increased fish production be estimated? Because benefits are measured by the willingness of people to pay for the change, the effects of the project on anglers, commercial fishers, and others must be estimated. Ideally, commercial fishing benefits attributable to the project would be estimated by the resulting increase in commercial fishing revenues (landed value) minus the resulting increase in commercial fishing costs. Because precise estimates of these revenues, and particularly these costs, are usually not available, average revenues and costs may be substituted. These figures are generally available for major commercial species, and average values probably differ little in the long run from values attributable to the project. If the increase in production is great enough to lower prices, the effects on consumers and producers must be considered. Producers benefit because they harvest more fish with the same effort, and consumers benefit from lower prices at the partial expense of producers. The net benefit may be approximated by multiplying the change in price by the average of total production before the change and total production after the change. Detailed econometric studies would be needed to estimate the benefits more precisely.

Angling benefits are estimated by the willingness of anglers to pay for the change. Because no traditional market for angling exists, however, project planners are often at a loss to estimate such values. Furthermore, if a market existed, the values of improvements in angling would vary greatly from site to site, much more like land values vary from place to place than like the relatively uniform values of commercial fish. The value to anglers of a given increase in fish production depends on the relative change in angling quality, the availability of substitutes similar to preproject and postproject angling quality, the availability of substitute kinds of angling, the preferences of anglers for the preproject and postproject kinds of angling, and the accessibility of the site to anglers. One method of estimating the change in angling value is to ask anglers directly how much they are willing to pay for the change. This method is subject to many pitfalls, however, and is not recommended without guidance from experienced researchers. Angler expenditures are not appropriate measures of project values because they measure the cost of angling rather than anglers' willingness to pay for a project. Willingness to pay for a project is an amount in excess of actual expenditures; it can be thought of as an access fee to use the site. For example, in Great Britain, angling rights are privately owned, and from 1973 to 1976 anglers in Scotland paid an average of $175 per fish to rent a section of river for salmon fishing.

Accurate estimates of angling values in the United States are now possible but expensive, requiring highly sophisticated econometric studies of angler travel and expenditure patterns or of anglers' responses to questions about hypothetical situations. An important caution is necessary here. Unless the study is specific to the project site or a site similar in the five respects mentioned in the previous paragraph, the project values will probably differ from the estimated values. Project value can vary that much, even within a restricted geographic area. In fact, by far most econometric studies of angling values estimate the values of choices that drastically differ from any of the choices usually considered by National Forest planners. Typically the studies estimate the all-or-none value of the fishery investigated — the willingness of anglers to pay to have the present fishery rather than not have it. This is an extreme value, and it is generally higher than most project values because projects on National Forests represent relatively minor changes in the overall fishery. Economists estimate all-or-none values because they are academically interesting and because they represent a clearly identifiable social choice, even if it has practically no direct significance to the projects. More detailed explanations of principles and procedures are available in Clawson and Knetsch (1966), Gregory (1972), and more vigorously in Talhelm (1973), Dwyer et al. (1977), and Freeman (1979).

This leaves the Forest planner with little information on which to estimate project benefits. Even the current values from the Forest and Rangeland Renewable Resources Planning Act used by the Forest Service are based on estimates of all-or-none values. Until better estimates are available, however, project planners have little choice but to follow Forest Service guidelines — as were used for our example, the Shasta Costa project.

Recent National legislation (National Forest Management Act of 1976, P.L. 94-588) requires use of fishery values (and values of other resources) in all land-use plans. The Forest Service, in compliance with P.L. 94-588 and the Forest and Rangeland Renewable Resources Planning Act (RPA), has developed a set of daily consumer benefits (table 3) for use in fishery valuation and economic analysis of habitat-improvement projects (USDA Forest Service 1979).

**Table 3 — Net consumer benefits for the USDA Forest Service 1980 Renewable Resources Planning Act Assessment (USDA Forest Service 1979)**

| Fishery | Consumer benefits/ angler-day | Consumer benefits/ commercial pound |
|---|---|---|
| | *Dollars* | |
| ANADROMOUS SALMONIDS | | |
| Sport benefits | 19.50 | — |
| Commercial benefits | — | 0.63 |
| Sport habitat improvement | 19.50 | — |
| Commercial habitat improvement | — | 0.80 |
| INLAND SPORT FISH | | |
| Cold water/warm water use | 5.25 | — |
| Cold water habitat improvement | 6.25 | — |
| Warm water habitat improvement | 4.25 | — |

RPA values (table 3) of $19.50 per angler-day for improving habitat for anadromous salmonids and $0.80 per pound for commercially caught salmon were used to estimate consumer benefits for the Shasta Costa project. The procedures are illustrated in figure 1. Most of the predicted net annual benefit of $8,300 is associated with increased production of fall chinook salmon and winter steelhead (table 4). Future evaluations should use the most recent daily consumer benefits recommended by USDA Forest Service. The project will remove about 5.8, 1.5, 10.0, and 8.0 percent, respectively, of the deficit in catch of fall chinook, coho, winter steelhead, and sea-run cutthroat that was expected in southwest Oregon by 1980.

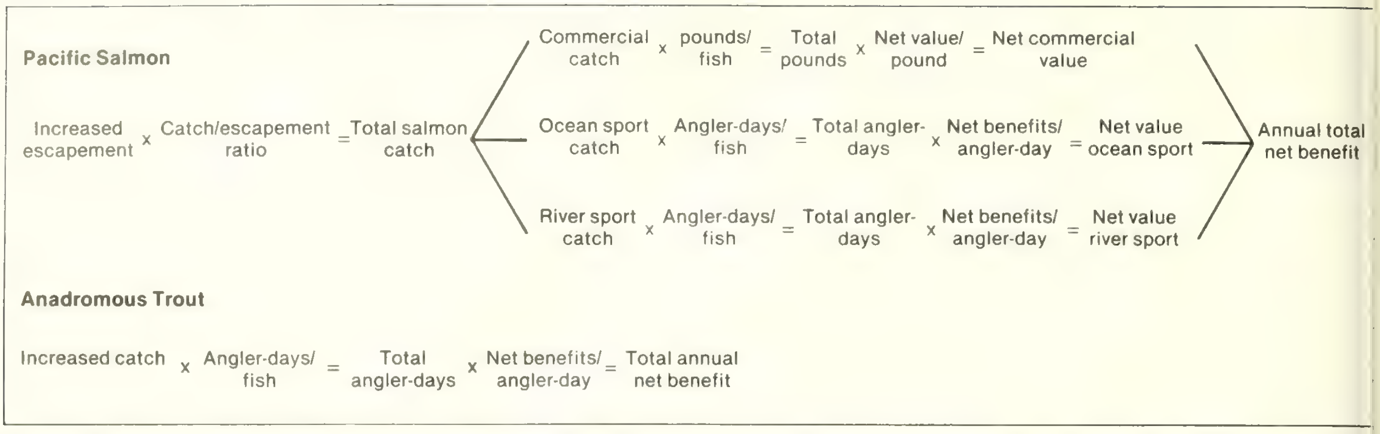
Pacific Salmon
Increased escapement x Catch/escapement ratio = Total salmon catch
Commercial catch x pounds/ fish = Total pounds x Net value/ pound = Net commercial value
Ocean sport catch x Angler-days/ fish = Total angler-days x Net benefits/ angler-day = Net value ocean sport
River sport catch x Angler-days/ fish = Total angler-days x Net benefits/ angler-day = Net value river sport
Annual total net benefit
Anadromous Trout
Increased catch x Angler-days/ fish = Total angler-days x Net benefits/ angler-day = Total annual net benefit

Figure 1. — Procedures for evaluating increased production of Pacific salmon and anadromous trout resulting from habitat improvement.

**Table 4 — Expected annual net economic benefits from laddering a natural barrier on Shasta Costa Creek, Siskiyou National Forest**

| Species | Increased catch | Net consumer benefits, sport | Net consumer benefits, commercial | Total net consumer benefits | "Catch deficit" relieved |
|---|---|---|---|---|---|
| | *Number* | *Dollars* | | | |
| Fall chinook | 200 | 1,360 | 1,210 | 2,570 | 5.8 |
| Coho | 50 | 330 | 190 | 520 | 1.5 |
| Winter steelhead | 100 | 4,680 | — | 4,680 | 10.0 |
| Cutthroat | 24 | 530 | — | 530 | 8.0 |
| Total | 374 | 6,900 | 1,400 | 8,300 | |

Costs associated with the project were also estimated. The Shasta Costa barrier, located 2 km from the nearest access road, is composed of a formation of bedrock and large boulders that creates a cascade about 3.2 m high. A concrete fishway, an aluminum Alaska steeppass, and a bedrock fishway created by blasting were considered possible alternatives for upstream passage of salmonids. Estimated construction costs of a conventional concrete fishway at this remote location exceeded $100,000, and the cost of a steeppass was about $25,000. Steeppasses, however, are easily clogged with debris and need frequent attention during freshets — a major disadvantage in a remote location. A fishway constructed by drilling, blasting, and adding minor supplemental weirs of concrete and reinforcing steel was easy to build at this location, economical, and required ittle maintenance. The estimated cost ncluded $930 for planning, $9,170 for construction, and $300 annually for maintenance (table 5). Because anticipated benefits were the same for all three construction techniques, the third alternative was selected.

Once costs and benefits have been estimated, project alternatives may be compared. Costs and benefits anticipated during the effective life of the project (considered to be 20 years in this example) may be listed in a table and discounted back to a common time, usually the year of construction. Discounting is necessary because a dollar today is worth more than the prospect of a dollar at some future date, and discounting determines the present worth of costs and benefits that are incurred or realized in the future. The present worth (discounted value) of a cost incurred in the future is calculated by use of the single-payment, present-worth factor by the formula:

$$P = S \frac{1}{(1 + i)^n},$$

where P = worth of the sum S, n years n the future at interest rate i. For example, the present worth of a $500 benefit expected 2 years in the future at 7-percent interest equals:

$$P = 500 \frac{1}{(1 + 0.07)^2} = \$437.$$

For a more detailed discussion of discounting, see Sheridan (1969) and Grant and Ireson (1970). A planner should use this standard method of discounting and the appropriate current interest rate to estimate present worth of project costs and benefits. In his example, we have used an interest ate of 7 percent as recommended by he Water Resources Council (1973) for water-related development projects table 6). The benefit/cost ratio (B/C) was derived by dividing discounted benefits by discounted costs. If the ratio is greater than 1, the project is conomically sound. The Shasta Costa roject, with a ratio of 4.33:1, appeared to be economically sound and highly esirable for development.

**Table 5 — Estimated costs of providing fish passage at a natural barrier on Shasta Costa Creek, Siskiyou National Forest**

| Activity | Cost |
|---|---|
| PROGRAM PLANNING | *Dollars* |
| 1 person-day | 80 |
| PROJECT PLANNING | |
| 11 person-days | 750 |
| Travel | 100 |
| CONSTRUCTION | |
| 40 person-days | 3,500 |
| Travel and per diem | 800 |
| Powder | 120 |
| Concrete, steel, wood | 500 |
| Equipment | 3,000 |
| Helicopter time | 750 |
| Administration | 500 |
| Maintenance, $300 annually | 5,700 |
| Total | 15,800 |

If a project B/C ratio is sensitive to changes in interest rates or to errors in estimated costs and benefits, especially if the ratio is near 1:1, the project is considered risky. For example, the Office of Management and Budget (OMB) requires that economic soundness of projects to improve fish habitat considered by the USDA Forest Service be assessed at a 10-percent discount rate. If a slight increase in interest rate changes the B/C ratio from a number greater than one (>1) to a number less than one (<1), the project might be questionable. To test its sensitivity to errors in cost and benefit measurement, the B/C ratio could be recalculated, for example, with the assumption that costs are up 10 percent and benefits are down 10 percent. If slight changes in benefits and costs change the B/C ratio from a number >1 to a number <1, the project might be marginal. Sensitivity analysis is highly recommended because estimates of project benefits are so uncertain.

**Table 6 — Discounted benefits and costs of the Shasta Costa project, Siskiyou National Forest, and benefit/cost ratio calculated at a discount rate of 7 percent**

| Year | Cost | Discounted cost | Benefit | Discounted benefit[1] | Discount factor @ .07 |
|---|---|---|---|---|---|
| | | | *Dollars* | | |
| 1 | 10,100 | 10,100 | 0 | 0 | .9346 |
| 2 | 300 | 280 | 0 | 0 | .8734 |
| 3 | 300 | 262 | 0 | 0 | .8163 |
| 4 | 300 | 245 | 4,150 | 3,166 | .7629 |
| 5 | 300 | 229 | 4,150 | 2,959 | .7130 |
| 6 | 300 | 214 | 4,150 | 2,765 | .6663 |
| 7 | 300 | 200 | 8,300 | 5,168 | .6227 |
| 8 | 300 | 187 | 8,300 | 4,831 | .5820 |
| 9 | 300 | 175 | 8,300 | 4,514 | .5439 |
| 10 | 300 | 163 | 8,300 | 4,219 | .5083 |
| 11 | 300 | 152 | 8,300 | 3,943 | .4751 |
| 12 | 300 | 143 | 8,300 | 3,685 | .4400 |
| 13 | 300 | 133 | 8,300 | 3,445 | .4150 |
| 14 | 300 | 125 | 8,300 | 3,219 | .3878 |
| 15 | 300 | 116 | 8,300 | 3,008 | .3624 |
| 16 | 300 | 109 | 8,300 | 2,811 | .3387 |
| 17 | 300 | 102 | 8,300 | 2,628 | .3166 |
| 18 | 300 | 95 | 8,300 | 2,456 | .2959 |
| 19 | 300 | 89 | 8,300 | 2,295 | .2765 |
| 20 | 300 | 83 | 8,300 | 2,115 | .2584 |
| Total | 15,800 | 13,202 | 128,650 | 57,227 | |

$$B/C = \frac{57{,}227}{13{,}202} = 4.33$$

[1] Costs are not discounted in year 1, but any benefits realized in year 1 are discounted.

The B/C ratio can be calculated perhaps most efficiently by using the USDA Forest Service, California Region (R-5) computer program, Invest III (USDA Forest Service 1972). The program allows use of three interest rates in determining B/C ratios and has internal provisions for testing sensitivity to changes in anticipated benefits and costs. Invest III sensitivity analysis for the Shasta Costa project indicated that the positive B/C ratio of 4.33 at 7-percent interest is not sensitive to slight changes in interest rate or costs and benefits. If costs are increased 10 percent and benefits reduced 10 percent, the B/C ratio is still a positive 3.55:1. At the OMB-recommended interest rate of 10 percent, the B/C is 3.35:1 and at 6 percent, 4.47:1. Invest III also estimates present net worth at three interest rates and the internal rate of return. The present net worth of the Shasta Costa project are $29,658, $44,057, and $50,253, respectively, at 10-, 7-, and 6-percent interest, and the internal rate of return is 26.6 percent. Figures 2 and 3 list Invest III data for the Shasta Costa project. For detailed information on Invest III, consult R-5 Invest III handbook (USDA Forest Service 1972).

The internal rate of return (IRR) assesses the relative payoff of a project. If a limited budget is available and projects being considered range greatly in size, the easiest way to select the group of projects with the greatest aggregate return within the budget is to compare internal rates of return. Simply rank projects by IRR, and choose the highest set possible within the budget.

Public review is often the final step in determining the soundness of a project. After physical, biological, and economic analyses are complete, an environmental analysis or an environmental impact statement must be written. If a project has a significant impact on the environment, it must have public review. Negative public response could result in a decision to defer or delete the project from further consideration. If the project survives public review, it is ready to be undertaken when funds become available.

For a complete analysis of improvement projects associated with barriers, other potential projects listed in table 2 should be subjected to the planning process. Detailed B/C and IRR analyses of each project should determine priority. Also, because habitat inventory on the Siskiyou is incomplete, the planning process must be kept open to accommodate new information as it is collected.

LONG-TERM INVESTMENT ANALYSIS

BENEFIT AND COST EFFECTIVENESS COMPARISON
(SEE INVEST III FAST VERSION USER GUIDE)

| CARD TYPE | ALT. NO. | BASE NO. | NAME OF FOREST ORGANIZATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | | | NAME OF UNIT | | | | | | | |
| | | | NAME OF USER | | | | | | | |
| | | | NAME OF PROBLEM | | | | | | | OMB RATE<br>OPT RATE<br>RANK RATE |
| | | | PROBLEM DESCRIPTION | | | | | | | |
| | | | SEQ. NO. | ITEM DESCRIPTION | PMT TYPE | YEAR | YEAR | TOTAL AREA | UNITS | COST OR INCOME DOLLARS |
| | | | | | | | | | | |
| | | | | | | | | | | |
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LONG-TERM INVESTMENT ANALYSIS

BENEFIT AND COST EFFECTIVENESS COMPARISON
(SEE INVEST III FAST VERSION USER GUIDE)

| CARD TYPE | ALT. NO. | BASE NO. | NAME OF FOREST ORGANIZATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 100 | SISKIYOU NATIONAL FOREST | | | | | | | |
| 2 | | 100 | NAME OF UNIT FISH AND WILDLIFE | | | | | | | |
| 3 | | 100 | NAME OF USER EVEREST | | | | | | | |
| 4 | | 100 | NAME OF PROBLEM SHASTA COSTA BARRIER 100 | | | | | | | OMB RATE<br>OPT RATE<br>RANK RATE |
| 5 | | 100 | PROBLEM DESCRIPTION SHASTA COSTA FISH PASSAGE FACILITY | | | | | | | 1000<br>0700<br>0700 |
| 6 | | | SEQ. NO.<br>1 | ITEM DESCRIPTION<br>1 CONSTRUCTION | PMT TYPE<br>01 | YEAR<br>000 | YEAR<br>001 | TOTAL AREA | UNITS | COST OR INCOME DOLLARS<br>-10.100 |
| 6 | | | 2 | 1 MAINTENANCE | 02 | 002 | 020 | | | -300 |
| 6 | | | 3 | 1 NET FISH BENEFITS | 02 | 004 | 006 | | | 4,150 |
| 6 | | | 4 | 1 NET FISH BENEFITS | 02 | 007 | 020 | | | 8,300 |
| 7 | | 100 | 1 | | | | | | | .10 |
| 7 | | 100 | 2 | | | | | | | .10 |
| 7 | | 100 | 3 | | | | | | | -.10 |
| 7 | | 100 | 4 | | | | | | | -.10 |

Figure 2. — Standard Invest III (USDA Forest Service 1972) form for benefit/cost analysis. Data are for the Shasta Costa project, Siskiyou National Forest.

Figure 3. — Simulated Invest III output data for benefit/cost analysis of the Shasta Costa project.

## Project Evaluation

The final element in program development — perhaps equal in importance to the steps discussed previously — is postdevelopment assessment of the accuracy of the cost and benefit estimates. Long-term projects may be assessed several times over their lives.

The Shasta Costa fishway construction was completed in 1978. Actual construction costs were $1,384 higher than estimated. The annual maintenance fee of $300/year is still anticipated to be correct. Increases in fish production cannot yet be measured, but the fishway is allowing fall chinook salmon and winter steelhead to pass upstream, and projected increases in production will probably occur. Based on the increase in construction costs and the probability that anticipated benefits will be realized, a postconstruction benefit/cost ratio (3.92:1) can be calculated at a 7-percent discount rate. Additional benefit/cost calculations should be made as actual increases in biological production are monitored over the next few years. Results of such evaluations are valuable in planning future projects to enhance habitat and improving precision of future benefit/cost analyses.

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Recent legislation (P.L. 93-452; P.L. 94-588) has emphasized improvement of fish and wildlife habitat on lands of the National Forest System. A sequential procedure has been developed for screening potential projects to identify those producing the greatest fishery benefits. The procedure — which includes program planning, project planning, and intensive benefit/cost analysis — has nationwide application for both fish and wildlife projects. Fisheries and wildlife values are difficult to assess and available estimates are far from ideal, but better estimates are gradually becoming available.

Keywords: Habitat improvement, wildlife habitat, cost/benefit evaluation, program planning, salmonids.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

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**Forest Service**

Pacific Northwest
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General Technical
Report
PNW-147

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# Predicting Lumber Volume and Value of Young-Growth True Firs: Users' Guide

Susan Ernst and W.Y. Pong

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## Authors

SUSAN ERNST and W. Y. PONG are research forest products technologists, Pacific Northwest Forest and Range Experiment Station, 809 N.E. Sixth Avenue, Portland, Oregon 97232.

## bstract

Ernst, Susan; Pong, W. Y. Predicting lumber volume and value of young-growth true firs: User's guide. Gen. Tech. Rep. PNW-149. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1982. 14 p.

Equations are presented for predicting the volume and value of young-growth red, white, and grand firs. Examples of how to use them are also given. These equations were developed on trees less than 140 years old from areas in southern Oregon, northern California, and Idaho.

Keywords: Lumber recovery, lumber yield, lumber value, young-growth stands, red fir, *Abies magnifica*, white fir, *Abies concolor*, grand fir, *Abies grandis*, volume determination, volume (merchantable).

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## Introduction

A significant proportion of the commercial true fir sawtimber volume in the West is in young-growth trees. As the old-growth timber is removed, young growth becomes more important as a raw material base for the timber industry. Log grades developed for old-growth timber do not adequately predict the volume or value of the young growth. Therefore, a new system using prediction equations to estimate volume and value of young-growth true firs was developed. This paper explains how this system can be used to predict the volume and value of lumber in standing young-growth true fir trees. These equations were developed from data on red fir (*Abies magnifica* A. Murr.) and white fir (*Abies concolor* (Gord & Glend.) Lindl. ex Hildbr.) in Oregon and California and on grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), in Idaho. Accuracy tests on a sample of 94 trees showed that predicted volumes and values were only 0.9 percent from actual volumes and 1.0 percent from actual values (Ernst 1982).

## Data

The data used to develop these equations were collected in studies conducted by the Timber Quality Research Project, Pacific Northwest Forest and Range Experiment Station, U.S. Department of Agriculture, Forest Service, Portland, Oregon. Trees were selected from National Forests and U.S. Department of the Interior Bureau of Land Management (BLM) lands in southern Oregon, northern California, and Idaho (fig. 1). The sample was selected from even-aged stands less than 140 years old and stratified by diameter at breast height (d.b.h.) and presence or absence of defect. D.b.h., total height, and crown class information were recorded, and the first 16 feet of each tree was diagramed (Jackson and others 1963, Pong and Jackson 1971). Logs from these trees were sawn into lumber, and the volume and grade of lumber from each tree were measured and recorded.

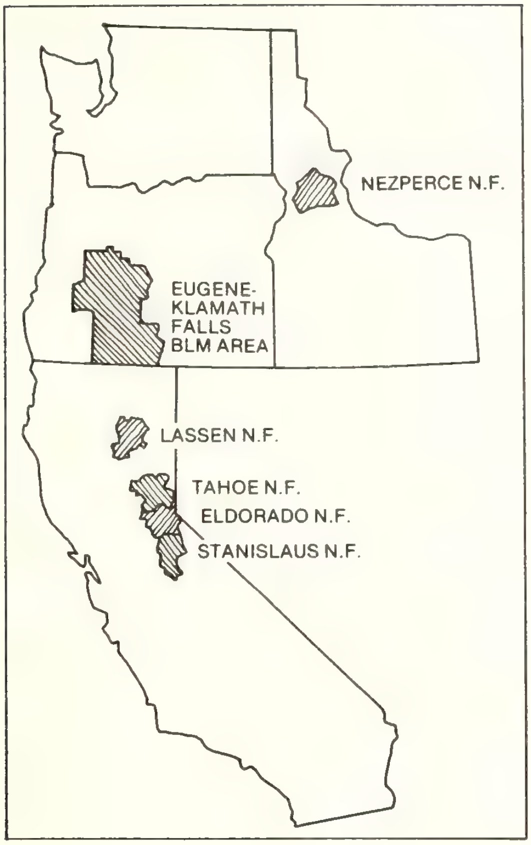

Figure 1.--Location of sample areas.

## thods

Similar to past approaches by Lane and others (1970), Snellgrove and others (1973), Plank and Snellgrove (1978), and Fahey (1980), two models were developed--one to predict lumber volume and one to predict lumber value. Unlike past approaches, lumber volume was derived from gross volume of the tree and the corresponding lumber recovery, each of which were modeled separately. An attempt to model defect separately proved unsuccessful because of limitations of the data. Two methods were used to model lumber value. The first predicted the volume of lumber in each lumber grade, and the second predicted an index of relative prices of the lumber grades. A detailed presentation of the modeling techniques used to develop the various equations is found in Ernst (1982).

The following basic steps and equations are used to predict the lumber volume and value of young-growth red, white, and grand firs; then a step-by-step example is provided.

## Lumber Volume

1. Field measurements

The first step is to obtain the following measurements:

a. Diameter at 4.5 feet on the uphill side of the tree (D);
b. Total height (H);
c. Presence or absence of defect (I) such as basal scars, lightning scars, conks, cankers, frost cracks, and snowbreaks;
d. Presence or absence of crook (C)--any abrupt deviation fro the main axis of the tree, especially pistol butt.

2. Estimates of gross cubic volume of trees

The second step is to choose and solve a gross cubic volume equation based on species and geographic location:

For WHITE and RED FIRS (WR) in northern California and souther Oregon:

$$VOL(WR) = D^2H(0.00159412 + 0.0025682(1/H) + 0.000000811(H^2/D)).$$

For GRAND FIR (G) in Idaho:

$$VOL(G) = D^2H(0.00187129 + 0.021574(1/H) + 0.000000755(H^2/D)).$$

3. Recovery estimates

The third step is to choose and solve a recovery equation. Recovery is defined as the cubic-foot volume of rough-green lumber produced from a cubic foot of the gross volume of a tree. Recovery equations vary by type of mill and species; therefore, mill users should use the appendix to determine th mill that most closely matches their own. A common equation (COMMON) is provided for those who are not using the estimate for a specific mill.

Recovery (REC) equations by mill (mills at Grangeville, Idaho; Burney and Martell, California; and Medford, Oregon) and species:

COMMON

$$REC = 0.628 - 6.751(1/D^{1.5}) - 0.203(I) + 0.00763(IH/{}^{0.5}).$$

Grangeville/grand fir

$$REC = 0.678 - 2.416(1/D) - 0.00037(IH/D) + 0.000044(IH^2).$$

Martell/white fir

$$REC = 0.295 + 10.047(1/D) - 177.580(1/D^2) + 0.0140(I) - 0.0980(C) + 0.666H/D^2.$$

Burney/white fir

$$REC = 0.674 - 1.735(1/D) - 18.950(1/D^2) - 0.0550(I) + 0.175(H/D^2).$$

Burney/red fir

$$REC = 0.610 - 23.980(1/D^2) - 0.310(I) + 0.050(IH/D).$$

Medford/white fir

$$REC = 1.0.$$

No specific recovery equation was developed for the Medford/white fir data group, so the recovery for that mill should be equal to 1.0.

4. Final correction coefficients

A final correction factor is applied to the product of gross cubic volume and recovery to predict the cubic-foot volume of lumber produced from each tree.

Final correction coefficients by mill and species--lumber volume ($ft^3$)= $B_1$(gross volume)(recovery):

| | $B_1$ |
|---|---|
| COMMON | 0.9713 |
| Grangeville/grand fir | .9386 |
| Martell/white fir | .9648 |
| Medford/white fir | .5068 |
| Burney/white fir | .9670 |
| Burney/red fir | .8354 |

5. Ratio of board feet to cubic feet of lumber

To enable the user to convert cubic feet of rough-green lumber to board feet of finished lumber, we estimated the ratio of board feet to cubic feet of lumber for each mill and species group and for all the data combined. The ratio of board feet to cubic feet of lumber (Fahey and Woodfin 1976) is the ratio of the board-foot volume of surfaced-dry lumber (nominal sizes) to the cubic volume of rough-green lumber (actual sizes). The board-foo volume of lumber is found by multiplying the cubic-foot volume of lumber in step 4 by the board-foot:cubic-foot ratio.

Ratios of board feet to cubic feet:[1]

| Mill/species | Ratio |
|---|---|
| COMMON | 13.844 |
| Grangeville/grand fir | 13.512 |
| Martell/white fir | 13.713 |
| Medford/white fir | 12.620 |
| Burney/white fir | 14.103 |
| Burney/red fir | 14.034 |

Results of each of the above steps for predicting lumber volume are illustrated for nine white fir trees in table 1. These trees were selected to represent a range of diameters from a lumber recovery study done in southern Oregon. Total height, diameter at breast height, and presence or absence of defect and crook for each tree are presented in the table. The calculations needed to predict the lumber volume are shown for the first tree, and the answers for the other eight trees are listed.

Predicted volumes were compared with the actual volumes to give some estimate of the reliability of these equations. Although the individual predicted lumber volumes may vary from the actual volumes, the volumes for the overall sample of nine trees had only a 0.3 percent difference between the actual and the predicted volumes. The variation in a larger test sample of 94 trees was only 0.9 percent (Ernst 1982).

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[1] One board foot of lumber in nominal sizes can be expressed as 1 by 12 inches by 1 foot, which in actual sizes could be 0.95 by 11.7 inches by 1 foot. In this example, the board-foot-per-cubic-foot ratio would be 1/(0.95x11.7/144) = 12.955.

Table 1--Results of the step-by-step approach to predicting lumber volume of standing white fir trees[1]

| Field measurements | | | | Gross tree volume[3] (VOL) | Recovery[4] (REC) | Lumber volume (LV) | | |
|---|---|---|---|---|---|---|---|---|
| D.b.h. (D) | Height (H) | Defect[2] (I) | Crook[2] (C) | | | Predicted[5] | Actual | Predicted[6] |
| Inches | Feet | | | Cubic feet | | - - Cubic feet- - | | Board feet |
| 7.7 | 56.4 | 0 | 0 | 6.60 | 0.31 | 1.99 | 0.81 | 27.55 |
| 9.0 | 44.9 | 1 | 0 | 6.67 | .29 | 1.88 | 3.11 | 26.03 |
| 10.5 | 54.2 | 0 | 0 | 11.16 | .43 | 4.66 | 2.34 | 64.51 |
| 11.7 | 63.2 | 0 | 0 | 16.54 | .46 | 7.39 | 9.09 | 102.31 |
| 13.1 | 67.2 | 1 | 0 | 22.05 | .42 | 9.00 | 8.37 | 124.60 |
| 15.1 | 79.2 | 0 | 0 | 35.46 | .51 | 17.56 | 17.90 | 243.10 |
| 16.0 | 94.9 | 0 | 0 | 50.48 | .52 | 25.50 | 29.27 | 353.02 |
| 18.8 | 72.9 | 1 | 0 | 47.89 | .47 | 21.86 | 18.49 | 302.63 |
| 23.5 | 128.5 | 0 | 0 | 154.98 | .57 | 85.80 | 86.86 | 1,187.82 |
| Total | | | | | | 175.64 | 176.24 | |

[1] Sample calculations for the 1st tree are in footnotes 3, 4, 5, and 6.

[2] 1 means defect or crook is present; 0 means absent.

[3] Equation for estimating gross cubic volume of red and white fir trees--

$$VOL(WR) = D^2H(0.00159412 + 0.0025682(1/H) + 0.000000811(H^2/D)).$$

$$VOL(WR) = (7.7)^2(56.4)(0.00159412 + 0.0025682(1/(56.4)) + 0.000000811((56.4)^2/7.7));$$

$$VOL(WR) = 6.60.$$

[4] COMMON equation for estimating recovery--

$$REC = 0.628 - 6.751(1/D^{1.5}) - 0.203(I) + 0.00763(IH/D^{0.5}).$$

$$REC = 0.628 - 6.751/(7.7)^{1.5} - 0.203(0) + 0.00763(0)(56.4)/(7.7)^{0.5};$$

$$REC = 0.31.$$

[5] COMMON equation for final correction coefficients for lumber volume--

$$LV\ (ft^3) = B_1(\text{gross cubic tree volume})(\text{recovery}).$$

$$LV\ (ft^3) = 0.9713(6.60)(0.31);$$

$$LV\ (ft^3) = 1.99.$$

[6] COMMON equation for lumber volume in board feet per cubic foot of lumber--

$$LV\ (bd\ ft) = \text{lumber volume } (ft^3) \times bd\ ft/ft^3 \text{ ratio}.$$

$$LV\ (bd\ ft) = 1.99(13.844);$$

$$LV\ (bd\ ft) = 27.55.$$

## Lumber Value

Two methods were developed to predict the total value of a tree. Both were developed to be used with current prices instead of having the prices built into the equation. The first method, volume by grade, is designed for users who wish to know the average volume of lumber in each grade produced from a tree with a given diameter. The second method predicts the total tree value by use of a relative index of lumber prices and volumes. It is much easier to use than the volume by grade method. Because the equations for these two methods were derived separately and predict either average volume by grade or total tree volume by use of a relative price index, the final total tree values may not be the same.

1. Volume by grade

Equations were developed to predict the average proportional volume (PV) of lumber in each lumber grade. These proportional volumes can be multiplied by the lumber volume of the tree and the current selling price for each grade of lumber--Standard and Better (Std & Btr), Utility (Util), and Economy (Econ)--to find the total tree value. Equations could not be produced for Medford/white fir, Martell/white fir, and Grangeville/grand fir data groups, so average PV's by grade across all diameters are given for them as follows:

| | Average proportional volumes | | |
|---|---|---|---|
| | Std and Btr | Util | Econ |
| Grangeville/grand fir | 0.857 | 0.029 | 0.114 |
| Martell/white fir | .713 | .080 | .207 |
| Medford/white fir | .780 | .068 | .152 |

The proportional volumes by grade did vary by diameter for Burney/white fir and Burney/red fir data groups and all the data combined, so equations were developed for these three data sets. The average PV's were made cumulative, so only two equations had to be developed to predict the three lumber grades. In this case, the PV of Economy lumber is found by subtracting the PV of Utility and Better (Util & Btr) from 100 percent. Likewise, the PV of Utility is found by subtracting the PV of Standard and Better from the PV of Utility and Better. The form of the final equation is as follows:

$$\text{Proportional volume in a given lumber grade} = 1.0/(1.0 + e^{(-(b_0 + b_1(D^2)))});$$

where, $e = 2.7182818$;

and constants by mill, species, and grade of lumber are:

| | | $b_0$ | $b_1$ |
|---|---|---|---|
| COMMON | Std and Btr | 0.574 | 0.00137 |
| | Util and Btr | 1.532 | .00355 |
| Burney/white fir | Std and Btr | .203 | .00250 |
| | Util and Btr | 1.146 | .00508 |
| Burney/red fir | Std and Btr | .317 | .00151 |
| | Util and Btr | 1.295 | .00314 |

Lumber values are predicted for the same nine trees using the volumes by grade method (table 2) and the relative index method (table 3). Again the calculations are shown for the first tree, and the answers for the other eight trees are listed in the tables. Predicted and actual prices are based on 1980 Western Wood Products Association prices, where the price of Standard and Better is \$210/M (\$210 per thousand board feet), Utility is \$129/M, and Economy is \$78/M.[2]

The predicted and actual values were also compared. Again, the individual tree values varied, but the overall sample predicted value varied only -5.4 percent from the actual value for the volume by grade method. The relative index predicted value varied -3.5 percent from the actual value for the overall sample. In another test of 94 trees, the variation for the relative index equations was only 1.0 percent.

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[2] Mention of companies or products is for the convenience of the reader and does not constitute an endorsement by the U.S. Department of Agriculture.

Table 2--Volume by grade method for determining lumber value in white fir trees, the step-by-step approach of predicting the proportional volume of lumber in each lumber grade[1]

| | Proportional volume by grade | | | | Total tree value[6] | |
|---|---|---|---|---|---|---|
| D.b.h. | Standard & Better[2] | Utility & Better[3] | Utility[4] | Economy[5] | Predicted | Actual |
| Inches | | | | | Dollars per thousand board feet | |
| 7.7 | 0.658 | 0.851 | 0.193 | 0.149 | 4.79 | 1.75 |
| 9.0 | .665 | .861 | .196 | .139 | 4.58 | 8.02 |
| 10.5 | .674 | .873 | .199 | .127 | 11.43 | 6.94 |
| 11.7 | .682 | .883 | .201 | .117 | 18.24 | 22.41 |
| 13.1 | .692 | .895 | .203 | .105 | 22.39 | 18.07 |
| 15.1 | .708 | .912 | .204 | .088 | 44.21 | 52.05 |
| 16.0 | .716 | .920 | .204 | .080 | 64.57 | 81.39 |
| 18.8 | .742 | .942 | .200 | .058 | 56.33 | 50.84 |
| 23.5 | .791 | .971 | .180 | .029 | 227.58 | 238.42 |
| Total | | | | | 454.14 | 479.89 |

[1] Sample calculations for the 1st tree are in footnotes 2, 3, 4, 5, and 6.

Proportional volume (PV) in a given lumber grade = $1.0/(1.0 + e^{(-(b_0 + b_1(D^2)))})$.

[2] COMMON equation--

PV in Std & Btr = $1.0/(1.0 + e^{(-(0.574 + 0.00137((7.7)^2)))})$;

PV in Std & Btr = 0.658.

[3] PV in Util & Btr = $1.0/(1.0 + e^{(-(1.532 + 0.00355((7.7)^2)))})$;
PV in Util & Btr = 0.851.

[4] PV in Util = PV in Util & Btr - PV in Std & Btr.
PV in Util = 0.851 - 0.658;
PV in Util = 0.193.

[5] PV in Econ = 1.0 - PV in Util & Btr.
PV in Econ = 1.0 - 0.851;
PV in Econ = 0.149.

[6] Value = total tree lumber volume (bd ft)(PV(Std & Btr)($/M)
+ PV(Util)($/M) + PV(Econ)($/M)).
Predicted value = 27.55 (0.658($210/M) + 0.193($129/M) + 0.149($78/M)).
Predicted value = 27.55 (0.658(0.210) + 0.193(0.129) + 0.149(0.078));
predicted value = $4.81.

2. Relative index equations by mill and species

The total tree value is found by predicting a relative index[3] of lumber prices and volumes and multiplying the relative index by the current price of Standard and Better lumber.

Relative index value = $B_0 + B_1$ lumber volume (bd ft).

| | $B_0$ | $B_1$ |
|---|---|---|
| COMMON | -5.510 | 0.9268 |
| Grangeville/grand fir | -4.312 | .9347 |
| Martell/white fir | -7.794 | .9348 |
| Medford/white fir | 2.368 | .8959 |
| Burney/white fir | -6.726 | .9103 |
| Burney/red fir | -.295 | .8640 |

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[3] The dependent variable (relative index value) was calculated this way: All the prices were made proportional to the price of Standard and Better. Then the actual lumber volumes in each grade were multiplied by these relative prices and added together. Thus, the index relates all the lumber volume to the price of Standard and Better.

Table 3--Results of the approach to predicting the tree value by the relative index method[1]

| D.b.h. | Relative index[2] | Predicted value[3] | Actual value |
|---|---|---|---|
| | | Dollars per thousand board feet | |
| Inches | | | |
| 7.7 | 20.02 | 4.20 | 1.75 |
| 9.0 | 18.61 | 3.91 | 8.02 |
| 10.5 | 54.28 | 11.40 | 6.94 |
| 11.7 | 89.31 | 18.76 | 22.41 |
| 13.1 | 109.97 | 23.09 | 18.07 |
| 15.1 | 219.80 | 46.16 | 52.05 |
| 16.0 | 321.67 | 67.55 | 81.39 |
| 18.8 | 274.97 | 57.74 | 50.84 |
| 23.5 | 1,095.36 | 230.02 | 238.42 |
| Total | | 462.83 | 479.89 |

[1] Sample calculations for the 1st tree are in footnotes 2 and 3.

[2] COMMON equation--
Relative index (RI) $= B_0 + B_1$ lumber volume (bd ft).
RI = -5.510 + 0.9268(27.55);
RI = 20.02.

[3] Predicted value = RI($/M Std & Btr).
Predicted value = 20.02 (0.210);
predicted value = $4.20.

## Metric Equivalents

1 foot = 0.3048 meter
1 inch = 2.54 centimeters
1 cubic foot = 0.02832 cubic meter

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# Appendix

The mill at Martell, California, had one 9-foot double-cut bandsaw with a 54-inch carriage, a 9-foot single-cut bandsaw with a 72-inch carriage, two edgers, one line-bar resaw, one trimmer, and a 24-tray automatic sorter. Mill production averaged 150,000 board feet of lumber per shift.

The mill at Medford, Oregon, had one single-cut, 7-foot bandsaw, a 4- by 66-inch single edger, a 32-foot gang trimmer, a twin-band vertical line-bar resaw, and a single band resaw on the green chain. Mill production averaged 90,000 board feet of lumber per shift.

The mill at Burney, California, had one quad-band headsaw, one debarker, one single-band resaw, two double-arbor edgers, one trimmer, an automatic drop sorter, and a lumber stacking and stickering machine. Mill production averaged 150,000 board feet of lumber per shift.

The mill at Grangeville, Idaho, one 9-foot, single-cut band headsaw, one 16-inch chip-n-saw, two debarkers, one twin-band resaw, one gang bull edger, two single edgers, one trimmer, and a drop sorter. Mill production averaged 150,000 board feet of lumber per shift.

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General Technical
Report
PNW-148

February 1983

# Competition for National Forest Timber: Effects on Timber-Dependent Communities

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## Names of Trees

| Common name | Scientific name |
|---|---|
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| Lodgepole pine | *Pinus contorta* Dougl. ex Loud. |
| Ponderosa pine | *Pinus ponderosa* Dougl. ex Laws. |
| Western larch | *Larix occidentalis* Nutt. |
| White fir | *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr. |

## Metric Equivalents

424 board feet, lumber tally = 1 cubic meter

221 board feet, Scribner scale = 1 cubic meter

# Competition for National Forest Timber: Effects on Timber-Dependent Communities

Richard W. Haynes
Technical Editor

General Technical Report PNW-148
February 1983

U.S. Department of Agriculture, Forest Service
Pacific Northwest Forest and Range Experiment Station
Portland, Oregon

# Abstract

Haynes, Richard W., tech. ed. Competition for National Forest timber: effects on timber-dependent communities. Gen. Tech. Rep. PNW-148. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 40 p.

Results are reported for three studies that dealt with the influence of timber sale practices on competition for timber in the timber-dependent communities of Medford and Grant County in Oregon and those surrounding the Nezperce National Forest in Idaho. Results are also reported for a fourth study that examines how several firms managed their uncut volume under contract. Although the description of the various local economies is only indicative of others, these studies point out the fragile nature of the economies of timber-dependent communities where most jobs, wages, and government services depend on the forest products sector.

Keywords: Timber sales, National Forest policy, National Forest administration, stumpage sales arrangements, economic impact.

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# 1. Introduction

## Richard W. Haynes

A last minute addition to the National Forest Management Act required the use of "sealed bidding on all (timber) sales except where the Secretary (of Agriculture) determines otherwise by regulations."[1] This mandate was the congressional reaction to the possibility of collusion on USDA Forest Service timber sales that were sold by oral bidding, and it led to a debate about the effectiveness of sealed bidding.

The debate was especially intense in California, Oregon, Washington, Idaho, and Montana where a history of oral bidding contributed to the development of local bidding patterns. These patterns evolved slowly and, in some cases, were the natural consequence of the local resource or market situations. In other areas, these patterns evolved as established firms attempted to control entry of new bidders (referred to hereafter as outside bidders) through the use of preclusive bidding. For example, established firms bid away either their locational advantage or cost advantage to prevent outside bidders from acquiring a particular sale.

The introduction of sealed bidding was seen by many as a threat to communities dependent on Federal timber. Oregon Senator Robert Packwood's description of the problem posed by universal use of sealed bidding was typical. He said (Congressional Record, p. S 17278, 9/30/76):

> In many areas of Oregon there is only one lumbermill in a town.

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[1] National Forest Management Act of 1976, Public Law 94-588, 94th Congress, S-3091-11.

ICHARD W. HAYNES is an economist, acific Northwest Forest and Range xperiment Station, U.S. Department of griculture, Forest Service, 809 N.E. ixth Avenue, Portland, Oregon 97232.

> The town depends upon the mill for employment. When the mill owner knows that he is going to be short of timber, he will go out and bid to the sky, if necessary, to keep that mill going. And so long as the bidding is open, he knows how high he has to go. But when the bids are sealed, that owner may put in what he regards as a very high bid, but if for some reason somebody bids higher, that owner does not get the timber and the mill shuts down.
>
> What you end up with is a mill out of timber and a town out of jobs solely because sealed bids rather than open bids are used.

The concern about sealed bidding is twofold: (1) that sealed bidding would lead to increased competition for timber sales and consequently higher bids, and (2) that sealed bidding would increase competition by outside bidders to the detriment of local communities. The second supposition led to modifications in the requirement that sealed bidding be used on all sales. The modifications permitted a mix of bidding methods consisting of about 75 percent oral bidding and 25 percent sealed bidding on sales, by volume of timber in areas tributary to adjacent dependent communities. In addition, if the volume purchased by firms with primary manufacturing facilities outside the adjacent dependent communities (outside bidders) equaled or exceeded the levels of previous purchases, then the proportion of volume sold by oral bidding could be increased.

These suppositions or hypotheses provided the stimulus for a research study with two objectives. The first objective was to assess competition for Forest Service timber under both oral and sealed bidding procedures. The second objective was to examine the relationship between timber flows from the National Forests and timber-dependent communities.[2] The assessment of competition was completed in 1978, and the results were published (Haynes 1979a, 1979b, 1980a, 1980b). This paper reports results of three studies that deal with the influence of timber sale practices on competition for timber in different timber-dependent communities. We also examine the rate at which some firms in the Forest Service Pacific Northwest Region (Region 6) harvest National Forest timber. The effect of the uncut volume under contract has often been ignored in the debates regarding the relationship between timber-dependent communities and Forest Service sale programs. In concept, however, timber volume already under contract may influence the effect of timber sale practices on competition for timber being sold.

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[2] This definition is from the Federal Register (42(106); 28258. Thursday, June 2, 1977):

> Dependent communities are areas with common social and economic interests bounded by established daily marketing and work force commuting patterns, and encompassing one or more primary wood products manufacturing facilities located within or adjacent to a specific area of National Forest timber upon which it is dependent for its timber supply and where 10 percent or more of the community work force is employed in the primary manufacture of wood products, including logging and log transportation, and National Forest timber accounts for at least 30 percent of the timber used in the primary wood products manufacturing facilities in the last five calendar years.

## Models of Stability

In forestry, it is difficult to divorce the dominant historical theme of community stability from discussions of public harvest flows. Stability in that sense is most frequently interpreted to mean evolutionary change (Schuster and others 1976). Communities evolve to some expected social state as economic and resource conditions change through time. Concerns about community stability reflect traditional forest management policies that were designed to promote social and economic prosperity of timber-dependent communities through the perpetuation of timber and related resources. These policies evolved into sustained yield management practices designed to promote continuity of harvest. The purpose here is not to argue the advantages or disadvantages of sustained yield as a harvest model but rather to discuss two common views of community stability associated with the concept. Also, keep in mind that these communities are typically dependent on the forest product industry for the major portion of their economic activity and on public timber for that industry's supply of timber.

The first view is that the availability of timber to firms operating in timber-dependent communities is a key determinant of community stability. In this view direct employment and income are created in proportion to output or production. In dependent communities, it is assumed that this direct economic activity constitutes a significant proportion of basic economic activity within the community and is also the dominant source of secondary or indirect economic activity. Community stability, in this context, is subject to the direct contributions of the forest-based products and to the directly linked secondary activity in supporting sectors. Finally, the direct and secondary activities induce economic activities primarily, but by no means exclusively, through respending by wage earners in the community.

Waggener (1969), Schuster and others (1976), and other investigators have suggested an alternative view of timber dependency and community stability that involves a more complex relationship between the aggregative timber sales program (over time and by ownership) and log inventory, together with a link between timber inventory, log markets, log supply, and production. These economic links in both the log and forest products markets are recognized as major determinants of timber inventory policy, influencing both additions to inventory and withdrawals from inventory. In this second view, the community stability concept is more dynamic than in the first approach, reflecting the interaction of the forestry-based sectors of the economy, as well as other basic sectors, and log and product inventory accumulation and adjustment, net investment, and the influence of national markets and economic policies.

Timber sales remain a significant factor but are put in context within a much more complex economic framework. Timber sales are more directly linked to timber and log inventory than to production, as in the conventional model. Additions to and withdrawals from timber inventory are conditioned by economic factors in addition to sales volumes. Production is seen as dependent on external market and economic factors, including monetary and fiscal policy. The second view, in contrast to the first, looks to external determinants to influence production decisions which, in turn, influence timber inventory withdrawals.

# The Case Studies

Three areas were used to study the influence of timber sale practices on competition for National Forest stumpage. These study areas were Medford and Grant County in Oregon and the area surrounding the Nezperce National Forest in Idaho. They were selected as representative of the types of communities considered dependent on National Forest timber. In these case studies, two questions raised by the introduction of sealed bidding were addressed. Both questions were reflected in the remarks of Senator Packwood, and both related to the possible destabilizing effects on timber-dependent communities of shifts from oral to sealed bidding methods. The first question deals with the effect of sealed bidding on stumpage prices in traditional timber markets. The second question is concerned with the influence of sealed bidding on increased competition from outside bidders. Changes in either stumpage prices or timber availability (resulting from successful outside bidders) have the potential to alter the economic health, or stability, of a timber-dependent community.

Each of these case studies examines the interaction between timber sales and community stability with a different approach and results. The Medford case study examines the origin of logs consumed in the Medford area for selected years between 1966 and 1976. It compares National Forest sale characteristics for 1975, 1976, and 1977 as a means of testing for impacts of the 1977 change to sealed bidding. The Grant County case study used a county input/output model, coupled with a linear programing model, to evaluate the effects of changes in stumpage in prices or quantities of stumpage on the local economy. The Nezperce case study examines the effects of sealed bidding on the timber sale programs of the Nezperce National Forest and on the surrounding communities.

A case study on a fourth area examines for three communities in Region 6 the relationships among timber sales, uncut volume under contract (sales purchased in past years but not yet harvested), and timber-dependent communities. The lag between purchase and harvest is a function of such factors as roadbuilding requirements, availability of logging crews and equipment, and levels of market activity for forest products. The proposition examined is that the uncut volume under contract serves as a buffer to mitigate the effects of losing a sale to a competing bidder.

One word of caution about interpreting the results of the various studies. The selected communities do not form a representative statistical sample. Rather they provide a cross section of all dependent communities. In that sense, the results and implications observed in each community are only indicative of what might be expected in other dependent communities.

# Sealed Bidding and Competition for National Forest Timber

This section contains a brief summary of three issues dealing with sealed bidding that were addressed in the assessment of competition for National Forest timber (Haynes 1980a) and influence the results reported for the case studies. The first was that the method of bidding influenced timber prices in areas characterized by little competition. Sealed bidding led to higher bids in the Northern Region (Region 1) of the USDA Forest Service and in the east side of Region 6 on sales between 2 million and 8 million board feet. Both of these areas were characterized by relatively low levels of competition. In addition, sealed bidding led to higher bids on the smallest and largest sales in the west side of Region 6. Elsewhere, sealed bidding led to higher overbidding, but the results were not statistically significant.

The second issue was that the mix of sealed and oral bidding methods actually used in 1977 may have resulted in higher prices than those before the switch to sealed bidding.[3] Empirical analysis demonstrated that the relationship between high bids and various sale characteristics remained unchanged for the entire period.

The third issue dealt with the probable impact of outside bidders on communities dependent on National Forest timber. These were bidders whose primary manufacturing facilities were located both inside and outside the "adjacent dependent community" but who had not in the past bid for local National Forest timber. The classification of bidders was subjective and based on the opinion of Forest Service personnel as to whether the bidder, because of location, would normally and traditionally be expected to bid on a particular sale.

The concern was that successful outside bidders would transfer logs from a dependent community to another community for processing. This would lead to a loss of processing jobs and adverse indirect impacts on the first community. Opponents of sealed bidding claimed that sealed bidding would increase the activity of outside bidders. Empirical analysis demonstrated that this was true only in the west side of Region 6. The supposition was not true in the east side of Region 6, which has always had a higher incidence of outside bidders than the west side. The higher incidence of outside bidders during 1977 also led to higher bids in both areas of Region 6 (Haynes 1980b).

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[3] During 1977 the USDA Forest Service offered timber sales by both oral and sealed bidding. The proportions of each method varied from Forest to Forest, depending on the degree of dependency of local communities on National Forest timber. In general, the smaller the dependency the greater the propensity of the Forest Service to use sealed bidding.

# Available Data From Forest Service Sales

Each study used timber sale data summarized from records for each sale made in the National Forest System. These records include four general variables: physical characteristics, cost and price information, bidder identification, and administrative variables.

The most common physical characteristics were total sale volume and species mix or proportion of the sale accounted for by a major species, such as Douglas-fir or ponderosa pine. Cost and price variables are volume-weighted averages for each sale and are expressed in thousand board feet, Scribner scale. The bidding price was adjusted for road costs for which the purchasers received a credit. Several of the studies used a variable termed "overbid" and defined as bidding price minus road costs and appraised stumpage. Overbid was used because it provides an absolute (real) measure of competition, as well as a consistent measure through time (Haynes 1979b). Number of bidders was the main bidder-related variable and was defined either as all bidders who qualified for bidding or as the actual number of bidders who actively bid. Administrative variables included sale location (Forest and District) and auction method (oral or sealed bidding).

# 2. The Medford Case Study

## J. Douglas Brodie and Lee E. Harris

This study analyzes three 1-year periods during the transition of sales method for the Medford area of southern Oregon.[4] The Medford area of southern Oregon is composed of the logging and manufacturing enterprises in Jackson and Josephine Counties and selected Ranger Districts of four National Forests in Oregon and three National Forests in California, on which these enterprises have bid for timber during the period. The years analyzed are fiscal years 1975 (July 1, 1974, to June 30, 1975) and 1976 (July 1, 1975, to June 30, 1976) and calendar year 1977 (January 1, 1977, to December 31, 1977). The last two quarters of calendar year 1976 were not analyzed because of transition problems during the switch from oral to sealed bidding. The National Forests and Ranger Districts for which sale data were analyzed are shown in figure 1. All Ranger Districts on the Rogue River National Forest were included, along with selected Districts where timber sale activity from enterprises in the Medford area has been noted on surrounding Forests. These Forests are the Umpqua, Winema, and Siskiyou in Oregon and the Six Rivers, Klamath, and Shasta-Trinity in California (fig. 1).

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[4] More detail is given in the report, "Trends in Timber Flow and Consumption in the Medford Area and Influences of Changes in Forest Service Bidding Method"; unpublished report on file at the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

J. DOUGLAS BRODIE is an associate professor and LEE E. HARRIS (deceased) was a graduate student, Department of Forest Management, Oregon State University, Corvallis, Oregon 97331.

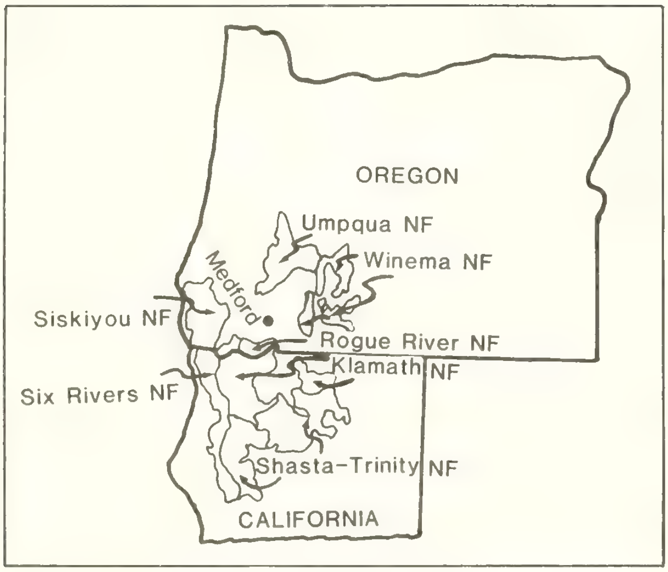

*Figure 1.--National Forests and Ranger Districts for which sales data were analyzed for the Medford case study.*

In the decade 1966 to 1976 log consumption in the Medford area declined (14 percent) as a consequence of declining public and private log supply (Austin 1969, Howard and Hiserote 1978). The sources of timber supply also shifted during this period, with greater quantities coming from Klamath County and California in 1976 than in 1966. The decline in log consumption did not affect the lumber and plywood industries equally. Log consumption by sawmills fell by 215 million board feet (41 percent), whereas log consumption by plywood mills increased by 98 million board feet (33 percent).

## Impacts of Forest Service Sale Characteristics and Bidding Methods

Standard Forest Service data on sale characteristics and bidders were obtained for all National Forest sales identified as part of the Medford area. These data were then used to examine the impacts of the switch from oral bidding to sealed bidding auction methods. In particular, two popular propositions (see Senator Packwood's statement in the introduction) about the switch to sealed bid auctions were examined. The first was that local bidders would be forced to bid to their maximum feasible price on a "one shot only" basis, possibly dissipating their profit and depreciation reserves. Second, outside bidders might be stimulated to participate in auctions since local bidders could no longer preempt them in the oral auction. If the outside bidders processed timber from their successful bids outside the local area, then the scarcity of timber in the local area might be intensified.

Both propositions can be examined empirically by treating comparisons of fiscal years 1975 and 1976 with calendar year 1977 as experimental evidence (only semicontrolled) for testing hypotheses. The first hypothesis is that sealed bidding should result in higher overbids. This hypothesis can be tested by use of available sale data.[5] The second hypothesis is that sealed bidding should increase the activity and success of outside bidders. Our ability to test this second hypothesis is limited in two ways.

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[5] Hypothesis tests with sales data used an "F" test for variance and a "t" test for means. The tests conducted were two-tailed, defining a probability range for which the null hypothesis cannot be rejected. Unless otherwise specified, the 5-percent level of significance is used throughout. For the t-test, the probabilities can simply be halved to test a hypothesis about the direction of differences. Both "pooled variance" and "separate variance" estimates were conducted.

First, the classification scheme for outside bidders is at best subjective. Second, the incidence of outside bidders has been increasing the last decade because bidders in southern Oregon have extended their participation in other timber markets to maintain adequate timber supplies.

## Auction Methods

Before calendar year 1977 and from 1978 to the present, the choice of oral bidding or sealed bidding was an administrative decision; both methods were used in various Forest Service Regions at the discretion of sale personnel. Within broad legislative guidelines sale procedures also vary between Regions and forest types. For instance, in the Pacific Southwest Region (Region 5), the several species on a sale have been traditionally bid with the auction going to the high cumulative bidder for all species. In Region 6 it has been traditional to bid for only a single major species, with expectations about minor species being lumped into this single bid. Before the mandate of sealed bidding in the National Forest Management Act of 1976, it was more common to use sealed bidding in Region 5 than in Region 6. Statistical tests performed on a larger number of sales in Region 5 than in the Medford area indicate that sealed bidding tended to be much lower than oral bidding in total volume and percent of major (premium) species during the discretionary 1975 and 1976 periods. Sealed bidding was used in small sales when its use was optional. During the 1977 period, when sealed bidding was mandatory unless relaxed because of local community dependency, sale characteristics were similar for both methods.

## Sales in the Medford Area

For the 3-year study period, 466 sales were analyzed in the Medford area; 154 sales occurred in fiscal year 1975, 152 in fiscal year 1976, and 160 in calendar year 1977. Table 1 shows the breakdown of these sales by method and illustrates the impact of the shift to sealed bidding in 1977. The dependent community provision for oral bidding was invoked for 47 percent of the sales in the Oregon part of the area and 13 percent in the California part during 1977.

Table 1--Number of Forest Service sales in the Medford, Oregon, area by method and Region, fiscal years 1975 and 1976 and calendar year 1977

| Sale method | USDA Forest Service Region | 1975 | 1976 | Total, 1975-76 | 1977 |
|---|---|---|---|---|---|
| Oral | 5 | 35 | 32 | 67 | 5 |
| | 6 | 113 | 107 | 220 | 58 |
| Sealed | 5 | 5 | 12 | 17 | 31 |
| | 6 | 1 | 1 | 2 | 66 |

Table 2 summarizes statistical tests for differences in Forest Service sale characteristics on the basis of sale method. During the discretionary years 1975 and 1976, there was a wide difference in the average total volume per sale--sealed bidding was used on only a few sales, and the average volume was only 4 percent of the average oral bidding sale size in 1975 and 7 percent in 1976. Sealed bidding auctions predominated in 1977. The average size of the sealed bidding sales was still significantly smaller, averaging 72 percent of oral bidding sales.

Table 2--Tests for differences in Forest Service sale characteristics in the Medford, Oregon, area by year and sale method

| Year and bidding method | Total volume | t value[1] | Overbid | t value[1] | Number of active bidders | t value[1] |
|---|---|---|---|---|---|---|
| | Thousand board feet | | Dollars per thousand board feet | | | |
| 1975: | | | | | | |
| Oral | 6,755.6 | 12.46* | 54.98 | 5.61* | 3.7 | 5.4* |
| Sealed | 267.3 | | 14.48 | | 1.7 | |
| 1976: | | | | | | |
| Oral | 7,165.6 | 12.20* | 58.25 | 1.21 | 4.2 | .60 |
| Sealed | 485.0 | | 40.85 | | 5.0 | |
| 1977: | | | | | | |
| Oral | 6,635.9 | 2.20* | 65.50 | 1.32 | 4.2 | 4.36* |
| Sealed | 4,746.3 | | 57.58 | | 6.0 | |

[1] Asterisk indicates that the null hypothesis of no difference at the 0.05 confidence level can be rejected on a single tail separate variance basis.

Sealed bidding sales had a significantly lower overbid in 1975, reflecting the differences in sale size and other characteristics. These differences were not significant in 1976 or 1977, but in each case were lower for the sealed bids. This comparison does not support a hypothesis of sealed bidding extracting higher returns for public timber or forcing purchasers to bid more recklessly than by oral bidding.

Sealed bidding and oral bidding were compared by number of active bidders, rather than total bidders. The distinction between active and total bidders applies primarily to oral bidding where many bidders qualify by submitting an appraisal-level bid in a preliminary sealed bid and then fail to raise their bid at the oral auction. For this study, these purchasers were classified as inactive bidders. In sealed bidding, qualification and bid occur simultaneously, and almost all bids are above appraisal so that active and total bidders are nearly always identical. In 1977, there was no difference between average number of total bidders in sealed and oral auctions, but there was a significantly larger number of active bidders in the sealed auctions.

## Conclusions

Differences within the Medford area.--Within the Medford area, there was (during the 3-year period) a significantly larger proportion of sealed bid auctions in California than in Oregon. Average sale volume was larger in California (62 percent in 1975 and 1976 and 17 percent in 1977). The sales in Oregon, however, contained more of one species (Douglas-fir) than did sales in California. There were no differences in average number of bidders per sale except in 1977 when there were more active bidders in Oregon.

There were slight differences among the four Oregon National Forests within the Medford area. There was very little sealed bidding before 1977. The Winema National Forest (an east-side Forest) differed from the three west-side Forests in that it had the least number of sealed bid auctions during 1977, largest average sale size, a greater mix of species, and generally less competition. Of the three west-side Forests, competition was least intense on the Siskiyou National Forest and most intense on the Umpqua National Forest. In general, the overbids were roughly equal for the west-side Forests and 42 percent higher in 1977 than those for the Winema National Forest.

These results do not support a hypothesis of higher financial recovery from sealed bid auctions relative to oral auctions because the overbid is lower, though not significantly so, on the sealed bid sales. Where competition for public stumpage is high, as indicated by the number of active bidders, either method extracts an overbid well above the Region 6 average.

Outside bidder activity.--The adoption of sealed bidding was accompanied by a more than doubling of the average number of outside bidders (9.3 percent of all bidders) during 1977. There was, however, no comparable increase in successful bidding by outsiders. Roughly 1 percent of the sales went to outside bidders in each of the 3 years.

Stumpage markets in the Medford area have been characterized by Haynes (1980a) as very competitive. In late 1976 the National Forest Management Act mandated a switch from oral to sealed bidding. Subsequent legislation in 1977 relaxed the requirement somewhat, but sealed bidding remained the predominant method during 1977. This switch precipitated considerable concern among National Forest bidders about price pressure on stumpage and loss of supply to outside bidders. Analysis presented in this study indicates that in a competitive market such as the Medford area, the sealed bidding method caused no price increase; however, the general upward trend continued. The switch in bidding method did cause an increase in activity by outside bidders but produced no increase in sales successfully purchased by outside bidders.

# 3. Grant County, Oregon: Impacts of Changes in Log Flows on a Timber-Dependent Community

## Frederick W. Obermiller and Lester F. Miller

In this chapter, the effects of changing Forest Service sales practices on the Grant County economy are evaluated. Grant County is a rugged and sparsely populated east-central Oregon county (fig. 2). In 1977 it depended on the forest products industry for 35 percent of total county employment, 24 percent of all goods and services sold, and 48 percent of all goods exported from the county. The forest products industry is, in turn, dependent for timber on the Malheur National Forest which accounts for over half the total county land area.

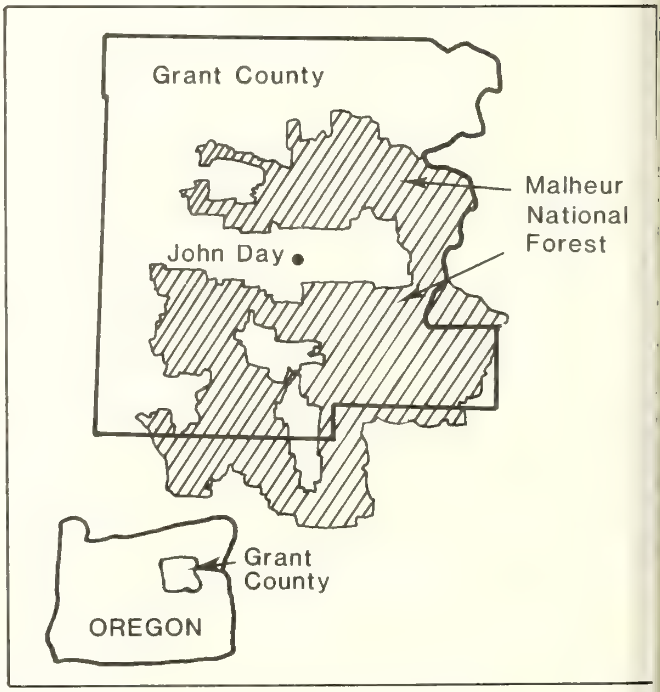

*Figure 2.--Grant County, Oregon.*

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FREDERICK W. OBERMILLER is an associate professor, Department of Agricultural and Resource Economics, Oregon State University, Corvallis, Oregon 97331. LESTER F. MILLER is an economist, Kootenai National Forest, U.S. Department of Agriculture, Forest Service, Libby, Montana 59923.

This evaluation required a methodology that considered both the structural and interindustry relationships among National Forest timber supplies, the forest products industry, and the Grant County economy. The methodology adopted combined input-output analysis and linear programing.[6] In the linear program, changes in stumpage prices and quantities are represented as changes in production costs or timber availability, and they affect the distribution of timber resources to processors and for other end uses. The direct and indirect effects of changes in log and lumber exports generate increased (or decreased) business income, wage income, or employment according to the input-output model. Consequently, the flow of information, or direction of impact, in this case study is from the local forest products industry to the broader local economy. Put differently, patterns of resource reallocation conditional on changes in National Forest System stumpage prices and availability of stumpage induce changes in economic activity throughout the local economy. Solutions from the linear programing model are used as inputs to the input-output model.

## The Grant County Economy in 1977

The economic interrelationships in Grant County demonstrate its reliance on manufacturing lumber for sale outside the county. Total sales for Grant County product groups (groups of similar economic sectors) in 1977 are given in table 3. Forest products, for example, accounted for 24 percent of all sales. The $45 million in forest products sales included $6 million in the timber hauling and harvesting sector, plus about $39 million in the lumber and wood products processing sector. Resource-based product groups (forest products and agriculture) accounted for 32 percent of all sales. The households product group contribution (25 percent) represented mainly wages, profits, and transfer payments such as social security. The remaining product groups contribute less to total business transactions in the county than do forest products and households.

Table 3--Sales, exports, imports, and wage income by product group and total value, Grant County, Oregon

| Product group | Sales | Exports | Imports | Wage income |
|---|---|---|---|---|
| | Percent | | | |
| Forest products | 24 | 48 | 13 | 44 |
| Households | 25 | 11 | 25 | 0 |
| Services | 18 | 8 | 24 | 16 |
| Other products | 14 | 10 | 23 | 5 |
| Government | 11 | 8 | 10 | 32 |
| Agriculture | 8 | 15 | 5 | 3 |
| Total | 100 | 100 | 100 | 100 |
| | Thousand dollars | | | |
| Total value | 188,185 | 68,800 | 78,953 | 24,676 |

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[6] Details on actual model construction are given in "Grant County Oregon: Impacts of Changes in Log Flows on a Timber Dependent Community," by Lester F. Miller; unpublished report on file at the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

The export base of Grant County (shown in table 3) is dominated by the resource-based product groups--forest products and agriculture. These two groups accounted for 63 percent of all sales outside the county in 1977. The remaining groups each accounted for about 9 percent of all products and services marketed outside the county.

Business imports for Grant County in 1977 are spread more evenly among product groups (table 3); both forest products and agriculture contributed proportionally less to total county imports. Imports were 15 percent (about $10 million) larger then exports in 1977, reflecting negative trade balances. Resource-based product groups accounted for only 18 percent of all outside purchases. Excluding "imports" of nonlocal government services (nonlocal taxes) of 10 percent, 72 percent of all outside purchases were attributable to nonresource-based businesses and households.

Wages paid by product groups also differ markedly in Grant County. As shown in table 3, wages paid by resource-based product groups accounted for 47 percent of all wages covered by the State Unemployment Insurance Law. The large proportion of wages attributable to government is the result of $5 million in State and Federal agency payrolls, especially those for local employment by the USDA Forest Service. Since these results include only covered payrolls and not proprietors' incomes, however, proportions reported for these two product groups may be overstated. The relative importance of wages paid in Grant County to individuals by resource-based industries and government, however, are probably representative of the prevailing situation in other eastern Oregon counties.

Within the forest products sector, the interrelationships between forest products firms and other product groups are oriented toward purchased transactions. The forest products firms, for example, account for a large proportion of total local input purchases (labor, electricity, taxes). Sales to other product groups by forest products firms are small relative to total sales. Also, nearly 11 percent of total sales of the sector in 1977 represented inventory accumulation.

The forest products group is made up of firms that are interrelated through timber resource flows. Wood processors purchase stumpage from government sources and logs from logging contractors. Log transactions between firms and logging contractors provide a short-term "dampening" effect when stumpage price or quantity relationships change.

# Empirical Results

The purpose of this section is to evaluate the local economic consequences of three possible timber supply and stumpage price scenarios. Here, the distribution of log flows, lumber production, business income, wage, and employment effects are projected by use of the linear programing model for these hypothetical changes in stumpage market activity.

## Impact Analysis of Changes in Stumpage Availability

Studies by Mead (1967) and Haynes (1980a) have indicated that the use of sealed bidding or the entry of outside bidders into timber markets can mean locally increased stumpage prices or decreased availability of stumpage. Such changes in local timber market activity ultimately affect the level of county export sales, the effects of which ripple throughout the economy.

The imposition of sealed bidding or entry of outside buyers is assumed in this study to increase stumpage prices or decrease local stumpage supplies from the levels of 1977. The effects of these assumed changes in the local timber market should be manifest as changes in local economic transactions. Of special interest are impacts on lumber and log exports, business income, wages, and employment.

Price or quantity relationships or both are assumed to fluctuate by 20 percent under these alternatives:[7] (1) a 20-percent increase in the maximum stumpage price on Forest Service timber sales, (2) a 20-percent decrease in the minimum stumpage available on these sales, and (3) a combination of (1) and (2).

Timber availability.--For each of the three assumptions, total stumpage volume available from the Malheur National Forest exceeded the annual production capacities of the existing mills. Most of the available timber was from timber sales let prior to 1977 (table 4). This sizable uncut volume under contract plus the existence of a log transfer market served as a "buffer" between short-run production requirements and potential timber market instabilities.

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[7] These amounts are for illustrative purposes. During 1977, the use of sealed bidding on the Malheur National Forest resulted in higher overbids (although not statistically significant) but roughly similar total bids. Higher overbids on sealed bidding sales were offset by lower appraised prices for sales offered by sealed bidding. These lower appraised prices resulted from a lower selling value (10 percent), among other things. Sealed bidding sales were also typically smaller than oral sales (2.1 vs. 7.5 million board feet). Also, during 1977 the activity of outside bidders tripled in Grant County although the level was still the lowest in eastern Oregon.

Table 4--Available stumpage volume utilized by Grant County, Oregon, timber processors, for the 1977 base year solution and the 3 alternatives

| Solution, alternative, and total | 1977 | | Previous years | | Total used in 1977 | |
|---|---|---|---|---|---|---|
| | Stumpage volume | Percent of total available | Stumpage volume | Percent of total available | Stumpage volume | Percent of total available |
| | Thousand board feet | | Thousand board feet | | Thousand board feet | |
| 1977 base year solution | 39,474 | 15 | 120,629 | 46 | 160,103 | 61 |
| Alternative 1 | 17,809 | 7 | 129,222 | 49 | 147,031 | 56 |
| Alternative 2 | 28,997 | 11 | 129,222 | 49 | 158,219 | 60 |
| Alternative 3 | 14,396 | 5 | 131,534 | 50 | 145,930 | 55 |
| Total stumpage available to Grant County firms | 91,370 | 35 | 172,184 | 65 | 263,554 | 100 |

The availability of uncut timber under contract at relatively lower prices and larger quantities leads to solutions that include stumpage from sales let prior to 1977. The base solution for 1977 indicated that the use of stumpage from prior year sales exceeded actual use of stumpage from prior year sales. As shown in table 4, about three-quarters of the estimated stumpage utilized in 1977 was attributable to sales from previous years. Also, the actual 1977 production requirements (used as the production constraint in the linear programing model) account for only 61 percent of available stumpage in the solution for 1977.

Under the three alternatives, the percentage of stumpage utilized declines, reflecting an increase in costs relative to revenues for local forest product firms. More significantly, the utilization of timber purchased in previous years increases by 8 to 11 percent as firms attempt to lower costs. The ability to buffer production against changes in stumpage markets is almost entirely limited to large firms (more than 100 employees) in Grant County. These firms control 97 percent of the uncut volume under contract. Small firms with little or no access to the uncut volume under contract are particularly susceptible to changes in stumpage prices as shown in table 5.

Independent loggers also respond to changes in stumpage market conditions (table 5). In the model solution process, a maximum annual volume transaction constraint of 9 million board feet was placed on these firms. There is considerable variation in stumpage distribution among species below this limit that results from different log transfer demands under each alternative. Under alternative 1 and 3 large firms increase their purchases of ponderosa pine from logging contractors. Under alternative 2 small firms increase their purchases of Douglas-fir--western larch and lodgepole pine from logging contractors.

Table 5--Distribution of stumpage from the Malheur National Forest, Oregon, for the base year 1977 and the 3 alternatives by type of firm, independent loggers, and species

| Type of firm, loggers, and species | Base year, 1977 | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|---|
| | Thousand board feet, Scribner scale | | | |
| Large firms:[1] | | | | |
| Ponderosa pine | 106,182 | 101,424 | 106,745 | 100,620 |
| Douglas-fir--western larch | 20,960 | 18,919 | 20,832 | 18,877 |
| White fir | 14,386 | 11,913 | 13,604 | 11,636 |
| Lodgepole pine | 5,017 | 4,007 | 4,607 | 4,032 |
| Total | 146,545 | 136,263 | 145,788 | 135,165 |
| Small firms: | | | | |
| Ponderosa pine | 509 | 220 | 220 | 220 |
| Douglas-fir--western larch | 965 | 553 | 696 | 553 |
| White fir | 83 | 10 | 33 | 10 |
| Lodgepole pine | 3,071 | 971 | 2,411 | 971 |
| Total | 4,628 | 1,754 | 3,360 | 1,754 |
| Loggers: | | | | |
| Ponderosa pine | 3,119 | 4,278 | 2,589 | 5,060 |
| Douglas-fir--western larch | 1,200 | 842 | 1,499 | 751 |
| White fir | 893 | 340 | 463 | 448 |
| Lodgepole pine | 3,788 | 3,540 | 4,449 | 2,741 |
| Total[2] | 9,000 | 9,000 | 9,000 | 9,000 |

[1] Firms with more than 100 employees.

[2] Maximum annual volume constraint of 9 million board feet.

Additional log supplies are available to firms, from net inventories, imports, and log transfers. These sources constitute 14 percent of total industry purchases, and each acts to moderate the impacts from changes in local timber market activity. Under each alternative, large firms maintain higher net inventories as a result of their production requirements than do smaller firms.

Lumber production, log exports, and net inventories.--Utilization of stumpage supplies in lumber production constitutes about 75 percent of all revenue generated in the forest products industry. The remaining activities, log sales for use outside the county and net accumulation of inventory, provide an additional market outlet for volumes not used in production and for short-term storage of excess log supplies.

The availability of stumpage from previous years and from the log transfer market enables large firms to maintain production at capacity for all alternatives. Solutions of the linear program indicate that price increases in local stumpage markets under alternatives 1 and 3 would restrict the availability of low value stumpage (white fir and lodgepole pine) to smaller firms, resulting in lower production levels (19 percent for alternative 1, 4 percent for 2, and 23 percent for 3). Although decreases in quantity (alternative 2) are less restrictive than increases in price, the differential price structure for stumpage still limits the available quantity of low value species.

In the linear programing model, the higher value of processed lumber compared with that of logs results in reduced log exports when stumpage prices increase. Net inventories are not appreciably affected by local changes in stumpage prices or by timber supplies. Logs in inventory are valued at the same market price as log exports in the model.

Neither production nor log exports by large firms are significantly affected by changes in price or quantity. The primary effect as indicated by solution of the linear programing model is the reduction in the output of small firms. This impact is the cumulative result of local changes in price and quantity, the availability of stumpage from other sources, and activities in the log transfer market.

Although production changes by Grant County wood products processors are the consequence of decreased availability of timber, net returns to the industry as a whole are not appreciably affected. Shifts in the prices and supply included in the three alternatives have the greatest impact on smaller firms, suggesting that in the short run the distributional consequences of sealed bidding may be more significant than the impacts on efficient production. In absolute terms, however, the industry-wide change in export activity over all price and quantity alternatives is slight.

## Regional Impacts Using the Input-Output Model

Changes in lumber and log exports from Grant County under each alternative are small in relation to total forest industry exports. These impacts affect regional business income, wages, and employment (table 6) through decreased direct and indirect local transactions. Export declines in excess of $2 million under alternatives 1 and 3 yield 3 to 4 percent decreases in total business income, wages, and employment within Grant County. Minimal declines in exports under alternative 2 result in correspondingly modest total impacts on the regional economy.

Table 6--Impact of changes in exports of lumber and wood products on business income, wage income, and employment in Grant County, Oregon, by product group, base year 1977, and alternatives

| Product group | Impact on business income | | | | Impact on wage income | | | | Impact on employment | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Alternative | | | | Alternative | | | | Alternative | | |
| | Base year | 1 | 2 | 3 | Base year | 1 | 2 | 3 | Base year | 1 | 2 | 3 |
| | Thousand dollars | Percent | | | Thousand dollars | Percent | | | Thousand dollars | Percent | | |
| Forest products | 56,541 | -5 | -1 | -5 | 13,895 | -5 | -1 | -5 | 930 | -5 | -1 | -5 |
| Households | 52,614 | -3 | -.4 | -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Services | 34,202 | -2 | -.3 | -2 | 4,197 | -2 | -.3 | -2 | 580 | -2 | -.3 | -2 |
| Other products | 27,840 | -1 | -.2 | -2 | 1,047 | -2 | -.3 | -2 | 208 | -1 | -.5 | -2 |
| Government | 24,012 | -3 | -.5 | -3 | 8,929 | -3 | -.5 | -3 | 853 | -3 | -.4 | -3 |
| Agriculture | 16,178 | -1 | -.1 | -1 | 803 | -1 | -.1 | -1 | 98 | -1 | 0 | -1 |
| Total or average (all sectors) | 211,387 | -3 | -.5 | -3 | 28,871 | -4 | -1 | -4 | 2,669 | -3 | -.5 | -3 |

These decreases are distributed predominantly among four product groups, excluding forest products: households, government, services, other products. In terms of business income other than household wages, the indirect effects on government, services, and other products account for the bulk of the impact on the regional economy. Declines in wage income and employment are primarily manifest in the forest products and government sectors which account for over 80 percent of all household income losses under each alternative.

Changes in production levels as a consequence of increased stumpage prices or decreased local timber supplies, or both, directly affect the regional economy. Results from the input-output analysis indicate that these changes reduce regional business income, wages, and employment by less than 5 percent from base-year levels.

## Summary

The economic stability of Grant County is dependent on use of natural resources. Lumber and log exports play a major role, contributing significantly to business income, wages, and employment. Changes in the stumpage market affect exports which in turn influence local economic transactions.

As processors, wood products firms in Grant County contribute heavily to the economic base. Since lumber and wood exports are based on local stumpage supplies, use of exogenous timber inputs (log imports) are minimized, resulting in a relatively large business income multiplier for the wood products industry. The high labor input levels associated with wood processing also result in this sector's having the largest wage income and employment levels of all sectors in the local economy.

Impacts on wood processing firms resulting from changes in prices and availability of stumpage have been shown to vary by size of firm. Timber availability under these conditions is most restrictive on smaller firms because of a higher overall cost structure and minimal uncut volume under contract. Increases in price of stumpage or declines in availability are accompanied by an increase in stumpage value and volume harvested by independent logging contractors. These results emphasize the significance of timber sales and log transfers from previous years, which act as a buffer against short-term adjustments in local stumpage markets.

Decreases in lumber exports, with corresponding declines in net returns, are primarily associated with low value stumpage and small wood processors. Log exports significantly decline for all species and firms, further reducing net returns. Relative to base-year levels, however, variations in these exports in absolute terms are small for the selected market condition alternatives.

Impacts on business income, wages, and employment resulting from changes in the stumpage market are also small when compared with the base-year simulation. Indirect effects on households and government product groups are relatively more pronounced. In the short term, existing uncut volume under contract can be expected to mitigate the destabilizing effect on timber-dependent communities of changes in price or quantity in local timber markets, or both. In the longer term, as uncut volume under contract and log inventories are exhausted, destabilizing impacts on income and employment, which could be associated with changes from oral to sealed bidding, would in all likelihood become more severe. The assumptions underlying the methodology used in this case study, however, are such that long-term analysis is precluded.

# 4. The Nezperce National Forest Case Study

## E. Lee Medema

This report analyzes the impacts of changes in sale procedures during 1977 on three timber-dependent communities adjacent to the Nezperce National Forest. One concern about increased use of sealed bidding was the effect it would have on the ability of local firms to compete for National Forest timber. The implication was that any change in sale procedures would have serious consequences in the various adjacent dependent communities.

The data analyzed included all sales over $2,000 (44 sales) sold by oral and sealed bidding methods on the Nezperce National Forest for fiscal years 1973 through 1977.[8]

## The Study Area and Communities

The Nezperce National Forest, located in central Idaho in the Forest Service's Northern Region (Region 1), contains 2,206,500 acres of National Forest lands, including 849,000 acres of commercial forest land (fig. 3). This is about 11 percent of the total National Forest acreage and 6 percent of the National Forest commercial forest land in the State of Idaho.[9]

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[8] More details are given in "Impacts of Forest Service Timber Sales on a Timber Dependent Community--The Nezperce Case" by E. Lee Medema, unpublished report on file at the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

E. LEE MEDEMA is an assistant professor, College of Forestry, University of Idaho, Moscow, Idaho 83843.

[9] U.S. Department of Agriculture, Forest Service. Land areas of the National Forest System. File 1380 (5400). Washington, D.C. 1978. 109 p.

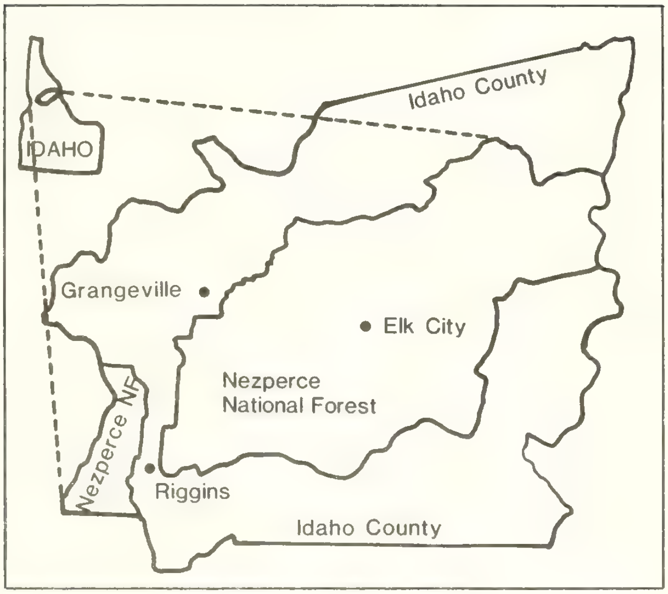

*Figure 3.--The Nezperce National Forest, Idaho County, and the timber-dependent communities.*

At the time of this study (1979), the Nezperce National Forest was mainly undeveloped, with 933,000 acres of inventoried roadless area being considered for possible wilderness designation and 735,000 acres in wilderness and primitive areas. The annual programed harvest was expected to average 100 million board feet in the late 1970's (Norman and others 1977). Between 1972 and 1977, the period of analysis for this report, the annual volume sold averaged about 78 million board feet, ranging from a high in calendar year 1972 of 138 million to a low in calendar year 1973 of 63 million. This volume comprises about 11 percent of the total annual sales from National Forest lands in the State of Idaho.

A dependency analysis conducted by the Nezperce National Forest in implementing the sealed bidding provision was used to define the dependent communities.[10] From this analysis, the dependent communities (defined in footnote 2, p. 2) were identified as the communities surrounding Grangeville, Elk City, and Riggins (fig. 3). Each of these communities satisfies the criteria for a dependent community (table 7).

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[10] "Dependency Analysis for the Nezperce National Forest"; unpublished report of the Forest Supervisor, Nezperce National Forest, to the Regional Forester, Region 1, Missoula, Montana, March 17, 1977.

Table 7--Results of analysis of 3 communities' dependence on timber, Nezperce National Forest, Oregon

| Community | Total community work force | Employment in wood products manufacturing | | Total community log input | Log input from Nezperce National Forest | |
|---|---|---|---|---|---|---|
| | | Work force | Percent of total | | Input | Percent of total |
| | - - - - Number - - - - - | | | Million board feet | | |
| Grangeville | 3,785 | 610 | 16 | 50 | 38 | 76 |
| Elk City | 364 | 136 | 37 | 20 | 19 | 95 |
| Riggins | 428 | 145 | 34 | 18 | 17 | 94 |

## Implementing Sealed Bidding on the Nezperce National Forest

The Forest Service implemented the sealed bidding provision in a manner that considered the degree of dependency of the local community on National Forest timber and existing mill inventories (including uncut volume under sale contract). It was determined that Grangeville was not as dependent on National Forest timber as were Elk City and Riggins. For timber sales in which either of the latter communities were the destinations for appraised timber, up to 49 percent of the volume sold could be offered by oral bidding. For timber appraised to Grangeville, however, the sealed bidding method would be used for all sales. These sale methodologies were implemented at the start of the 1977 calendar year.

Effective July 1, 1977, the Forest Service developed a new system of implementing the sealed bidding provision. On the Nezperce National Forest, this system was designed to achieve about 75 percent oral bidding and 25 percent sealed bidding in terms of volume sold for all sales offered regardless of the degree of dependency of the appraised destination. This system was used for the remainder of calendar year 1977 and until May 1978, when the sealed bidding provision was amended.

These changes in the implementation procedure for the sealed bidding provision both among the dependent communities and through time complicate the analysis. To reduce confounding errors in interpretation, only the first period from January 1, 1977, to June 30, 1977, was treated as the "implementation period" in testing the various arguments of the opponents of sealed bidding.

The total volume sold by oral bid for the 42-month period before implementation of the sealed bidding provision was 67 percent for Grangeville, 41 for Elk City, and 73 for Riggins. Oral bidding was the predominant method used to sell the majority of the volume appraised to the Grangeville and Riggins communities. For sales appraised to the Elk City community, however, the majority of the total volume was sold by sealed bidding.

During the implementation period no sales appraised to the Grangeville community were sold by oral bidding. For the two sales appraised to the Elk City community, the largest (19.2 million board feet) was sold by oral bidding. No sales were appraised to the Riggins community during the implementation period.

The change in sale procedures to favor sealed bidding had little effect on sale methods for timber appraised to these three communities. Only in the Grangeville community did the changes result in a shift in bidding methods from oral to sealed.

## Testing Specific Concerns About the Effects of Sealed Bidding

The effects of sealed bidding were frequently described in terms of changes in stumpage prices resulting from increased (or more effective) competition. In the dependent communities around the Nezperce National Forest, the concerns about sealed bidding (discussed in the "Introduction") can be expressed as three hypotheses that can be tested by use of sale data. These hypotheses are:

1. Sealed bidding results in higher bidding prices.
2. Sealed bidding results in an increase in the activity of outside bidders.
3. Sales with outside bidders have higher bidding prices than sales with no outside bidders.

A t-test procedure (see footnote 5, p. 8) was used to test each hypothesis.. The null hypotheses were that:

1. During the implementation period, sealed bidding resulted in no change in bidding prices from those observed before the implementation period.
2. During the implementation period, sealed bidding resulted in no increase in the activity of outside bidders from that observed before the implementation period.
3. During the entire data period, sales with outside bidders had the same bidding price as other sales.

The available data (44 sales) for testing these hypotheses are divided among the three communities by bidding method:

| | Before the implementation period | | During the implementation period | |
|---|---|---|---|---|
| | Oral | Sealed | Oral | Sealed |
| Grangeville | 11 | 10 | 0 | 3 |
| Elk City | 2 | 8 | 1 | 1 |
| Riggins | 5 | 0 | 0 | 3 |

The lack of any sales by sealed bidding before the implementation period prevented testing the first two hypotheses in the Riggins community. The results for the second hypothesis in the Elk City community have to be interpreted with caution because only one of the two sales appraised to the community was sold by sealed bid.

The results of these tests are as follows:

| Hypothesis | Grangeville | Elk City | Riggins |
|---|---|---|---|
| 1 | Reject | Reject | Not tested |
| 2 | Reject | Reject | Not tested |
| 3 | Accept | Accept | Accept |

The first two hypotheses deal with the effects of sealed bidding. In the first hypothesis, sealed bidding did not lead to higher bid prices in either the Grangeville or the Elk City community. The increased activity of outside bidders expected (hypothesis 2) after the implementation of sealed bidding also did not occur. The number of outside bidders per sale in the Grangeville community was the same for both the historical and implementation periods. In the Grangeville community, however, the number of outside bidders per sale was significantly larger for sales by sealed bidding than by oral bidding.

The third hypothesis deals with the assumption that sales with outside bidders have higher bids than sales with no outside bidders. For sales appraised to each community during the entire data period, all the testable results yielded significant differences--sales by both oral and sealed bidding had significantly higher bids when there were outside bidders than sales with no outside bidders.

Outside bidders appear to be the major source of competition for sales appraised to each of the dependent communities relative to internal competition among local bidders. In the period analyzed, no sales contained more than one local bidder for sales appraised to the Grangeville or the Elk City community, and only one sale had more than one local bidder for sales appraised to the Riggins community. In the Grangeville community, the average number of outside bidders per sale (on sales with more than one bidder) was always greater than the average number of local bidders.

One could hypothesize that the above results may have been distorted by changes in average sale characteristics before and during 1977. This question was examined for each hypothesis and community. Only in the third hypothesis did the sale characteristics differ in such a way as might bias the bidding prices upward. In this case, sales with outside bidders had a significantly lower average selling value per sale and a significantly greater average number of bidders per sale.

Similarly, for oral bidding sales appraised to the Grangeville community and for sealed bidding sales appraised to the Elk City community, the average number of bidders per sale on sales with outside bidders was significantly larger than for sales with no outside bidders. Again, this could have biased the bidding price upward.

## Conclusions

The implementation procedure for the sealed bidding provision of the National Forest Management Act of 1976 was designed to have sealed bidding as the predominant bidding method for sales appraised to the three communities dependent on the Nezperce National Forest for a supply of timber. This resulted, however, in a change in the mix of bidding methods from one dominated by oral bidding to one dominated by sealed bidding in only one of the dependent communities--the Grangeville community. For the other dependent communities, either sealed bidding was historically the predominant bidding method used, or no sales were sold during the implementation period.

Where the mix of bidding methods was changed to one of predominantly sealed bidding, no increase in the activity of outside bidders and no increase in bidding prices were evident. Outside bidders, however, did exhibit a greater propensity to bid on sealed, rather than oral, bidding sales, and the bidding prices on sales with outside bidders was significantly larger than on sales with no outside bidders.

# 5. Interaction Between Timber Sales, Uncut Volume Under Contract, and Timber-Dependent Communities

## Thomas R. Waggener

Throughout the legislative history of the National Forest Management Act of 1976 and the subsequent regulations and amendments, there has been a tendency to assume that any deviation in the pattern of timber sales among potential buyers constitutes a threat to the economic stability of a dependent community. The truism that a mill cannot produce lumber and other wood products if it does not have a supply of logs has been traditionally set forth as "proof" that less wood means economic instability. From this, it is asserted that the continued production of a mill is dependent on individual timber sales--and hence the economic stability of the community is threatened by a potential mill closure (permanent or temporary) necessitated by the short fall of timber supply.

This chapter has two objectives. The first is to examine how specific firms manage their uncut volume under contract. The purpose is to put individual sales into perspective and to examine whether individual sales are critical to the economic health of both a firm and the community in which it operates. The second objective is to examine for three timber-dependent communities the links between individual timber sales, economic conditions, and uncut volume under contract. These links will be examined for the communities of Packwood-Randle in Washington and Baker and Union in Oregon. The period of examination is December 1974 to September 1977.[11] This period covers the interval just before enactment of the Forest Management Act of 1976 and the initial period of the sealed bidding policy.

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THOMAS R. WAGGENER is a professor, College of Forest Resources, University of Washington, Seattle, Washington 98195.

[11] More details are given in the report, "Timber Sales, Uncut Inventory and Timber Dependent Communities," by Thomas R. Waggener; unpublished report on file at the Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

# How Selected Firms Manage Uncut Volume in Three Communities

## Packwood-Randle, Washington

The communities of Packwood and Randle in Lewis County, Washington, are surrounded by the Packwood and Randle Ranger Districts of the Gifford Pinchot National Forest. The major forest products firms in these two communities are Packwood Lumber Company at Packwood, Cowlitz Stud Company, Mt. Adams Veneer Company, and R.D.W. Manufacturing at Randle. Of these firms, the Packwood Lumber Company was selected for detailed examination.

Discussions with Packwood Lumber representatives indicated that Pacific Timber Company of Seattle operated both the Packwood Lumber Company in Packwood and Cowlitz Stud Company in Randle. As a consequence, the combined purchases of the Packwood Lumber Company, Pacific Lumber and Shipping Company, and Pacific Lumber Sales Company were aggregated for the two Ranger Districts and treated as a single firm in this analysis.

Timber purchases in the Packwood and Randle Ranger Districts by the Pacific Timber Company are summarized in table 8. There was a total of 384 timber sales active on the two Ranger Districts during the period January 1975 through September 1977, with an appraised volume of 1,440 million board feet. Of this total, 244 sales with a volume of 975 million board feet were sold before 1975 but remained active after that date. The Pacific Timber Company was the purchaser of 73 sales, with a volume of 410 million board feet. This represented almost 19 percent of sales and 28.6 percent of volume sold. Excluding sales before 1975, these firms purchased 20 sales (14.3 percent) with a volume of 113 million board feet (24.3 percent) during the 1975-77 period.

The disposition of timber purchases by the Pacific Timber Company is also shown in table 8. For the Packwood and Randle Districts, a total of 209 million board feet purchased before 1975 was actually harvested before 1975, leaving an estimated balance of 101 million board feet as uncut inventory.[12] Although 53 sales were purchased before 1975 and shown as active after January 1975, the actual uncut volume was contained on only 28 sales. Thus, 25 sales had been harvested before 1975, yet the sales remained active on Forest Service records although no further volume was harvested.

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[12] Because of datum problems, uncut volume remaining under contract cannot be determined directly by subtracting cut from purchases. Purchases are estimated volumes, whereas cuts are actual volumes. Uncut volumes discussed here have been corrected to the extent possible for differences in original estimates of volume and subsequent harvests.

Table 8--Total sales and volumes of timber sold and purchased, and sales and volumes purchased by the Pacific Timber Company, Packwood and Randle Ranger Districts, Gifford Pinchot National Forest, December 31, 1974, to September 30, 1977

| Date | Total sales | Total volume | Purchased by Pacific Timber Company | | | |
|---|---|---|---|---|---|---|
| | | | Sales | Volume | Cut | Uncut volume under contract[1] |
| | Number | Million board feet | Number | - - - Million board feet - - - - | | |
| 12/31/74[2] | 244 | 975 | 53 | 296 | 209 | 101 |
| 12/31/75 | 52 | 164 | 5 | 44 | 32 | 109 |
| 6/30/76 | 23 | 76 | 7 | 10 | 7 | 112 |
| 9/30/76 | 9 | 22 | 3 | 8 | 13 | 107 |
| 3/31/77 | 25 | 52 | 2 | 9 | 9 | 106 |
| 9/30/77 | 31 | 150 | 3 | 42 | 15 | 133 |

[1] Includes only volumes removed by harvest from appraised volumes.

[2] Active sales reported 12/31/74, including sales offered in 1974, as well as sales sold in preceding years but not completely harvested.

## Baker, Oregon

Baker, located in Baker County in northeastern Oregon, is dependent on the Baker Ranger District of the Wallowa-Whitman National Forest for the timber to support the forest products economy of the region and community. The Ellingson Lumber Company and the Ellingson Timber Company comprise the major forest products firms within the community. The Ellingson companies operate both a sawmill and a softwood veneer mill.

Table 9--Total sales and volumes of timber sold and purchased, and sales and volumes of timber purchased by the Ellingson Lumber and Timber Companies, Baker Ranger District, Wallowa-Whitman National Forest, December 31, 1974, to September 30, 1977

| Date | Total sales | Total volume | Purchased by the Ellingson Lumber Company and the Ellingson Timber Company | | | |
|---|---|---|---|---|---|---|
| | | | Sales | Volume | Cut | Uncut volume under contract[1] |
| | Number | Million board feet | Number | - - - Million board feet - - - - | | |
| 12/31/74[2] | 16 | 106 | 9 | 64 | 58 | 18 |
| 12/31/75 | 9 | 33 | 2 | 21 | 16 | 22 |
| 6/30/76 | 1 | 3 | 1 | 3 | 9 | 39 |
| 9/30/76 | 3 | 1 | 1 | 1 | 1 | 39 |
| 3/31/77 | 2 | 10 | 2 | 10 | 15 | 36 |
| 9/30/77 | 6 | 37 | 6 | 37 | 17 | 56 |

[1] Includes only volumes removed by harvest from appraised volumes.

[2] Active sales reported 12/31/74, including sales offered in 1974, as well as sales sold in preceding years but not completely harvested.

Timber sale purchases on the Baker Ranger District are summarized in table 9. A total of 37 timber sales were active on the Baker Ranger District during the period 1975 through the third quarter of 1977, with a volume of 190 million board feet. Sixteen of these sales were sold before 1975, accounting for a total volume of 106 million board feet. The Ellingson Timber Company purchased 21 of the total active sales, totaling 136 million board feet.

The utilization of timber sales purchased by Ellingson Lumber Company and Ellingson Timber Company is also summarized in table 9. This summary does not include three sales on the Union Ranger District of the Wallowa-Whitman National Forest.

Ellingson Timber Company purchased a total of 11 sales (9 on the Baker Ranger District (table 9), 2 on the Union) before 1975, with a total volume of 77 million board feet, which were still active in 1975. Of these sales, seven were totally harvested before 1975 even though reported as active. Total cut on all active sales as of December 31, 1974, was 58 million board feet, and uncut volume was 18 million board feet.

Table 10--Total sales and volumes of timber sold and purchased, and sales and volumes of timber purchased by the Hoff-Ronde Valley Lumber Company, Union Ranger District, Wallowa-Whitman National Forest, December 31, 1974, to September 30, 1977

| Date | Total sales | Total volume | Purchased by the Hoff-Ronde Valley Lumber Company | | | |
|---|---|---|---|---|---|---|
| | | | Sales | Volume | Cut | Uncut volume under contract[1] |
| | Number | Million board feet | Number | - - - Million board feet - - - - | | |
| 12/31/74[2] | 14 | 88 | 5 | 35 | 15 | 21 |
| 12/31/75 | 4 | 12 | 2 | 3 | 8 | 16 |
| 6/30/76 | 3 | 26 | 2 | 5 | 5 | 20 |
| 9/30/76 | 0 | 0 | 0 | -- | 3 | 17 |
| 3/31/77 | 4 | 19 | 2 | 13 | 8 | 22 |
| 9/30/77 | 3 | 8 | -- | -- | 3 | 18 |

[1] Includes only volumes removed by harvest from appraised volumes.

[2] Active sales reported 12/31/74, including sales offered in 1974, as well as sales sold in preceding years but not completely harvested.

## Union, Oregon

Union, Oregon, is in Union County about 35 miles north of Baker and is primarily dependent for timber on the Union Ranger District, Wallowa-Whitman National Forest. The primary forest products manufacturing facility in Union is a sawmill operated by the Hoff-Ronde Valley Lumber Company, a subsidiary of the Hoff Company, Inc., of Boise, Idaho.

Timber purchases by Hoff-Ronde Valley Lumber Company in the Union Ranger District are shown in table 10. A total of 28 timber sales were reported as active on the Union Ranger District, with a volume of 153 million board feet. Half of these sales (14) were sold before 1975, accounting for 88 million board feet (58 percent) of total sales volume. The Hoff-Ronde Valley Lumber Company was the purchaser of 11 sales (39 percent of all sales) with a volume of 56 million board feet (37 percent). Exclusive of sales before 1975, Hoff-Ronde purchased 6 of 1 sales with 21 million board feet.

The Ellingson Lumber Company also purchased three sales on the Union Ranger District, with a total volume of 34 million board feet. Two sales were purchased before 1975; and one large sale (21 million board feet) was acquired in the first half of 1976, accounting for almost 80 percent of volume sold during that period.

## General Economic Conditions in the Three Dependent Communities

The 1975-77 period represented a variable economic picture as the backdrop for the activities of the forest products industry in the Pacific Northwest. The economy had been growing reasonably steadily after a slight decline at the end of 1970 until a peak in late 1973 and early 1974. A general downturn occurred in 1974, continuing through the first quarter of 1975. This was followed by a period of growth, beginning in the second quarter of 1975 and extending through the third quarter of 1977.

The broad trends in economic activity are reflected in the number of housing starts, which is generally considered a major determinant of forest products markets. Housing start activity for 1973-77 is shown in figure 4 and is characterized by a strong upward trend from 1975 to 1977, reaching nearly the 2 million level achieved in 1971-73.

Lumber and plywood production and prices reflected the trend in housing construction. Both prices and production recovered from the depressed 1974 levels and rose throughout the 1975-77 period. This rise in product prices was interrupted twice by brief economic slowdowns, but prices by the end of the period were 43 and 52 percent higher for plywood and lumber.

The economies of the study communities reflect the emphasis on timber-oriented activities. This is illustrated in table 11 for the counties containing the three dependent communities. In general, the forest products industry (represented by logging and wood products manufacture) accounted for the bulk of manufacturing jobs in each county. The annual variability in employment can also be gaged from table 11. Employment levels were lowest in 1974 and increased in subsequent years as construction and economic activity improved. Similar trends for payrolls are also shown, although inflationary increases in prices and wages mask actual trends in employment.

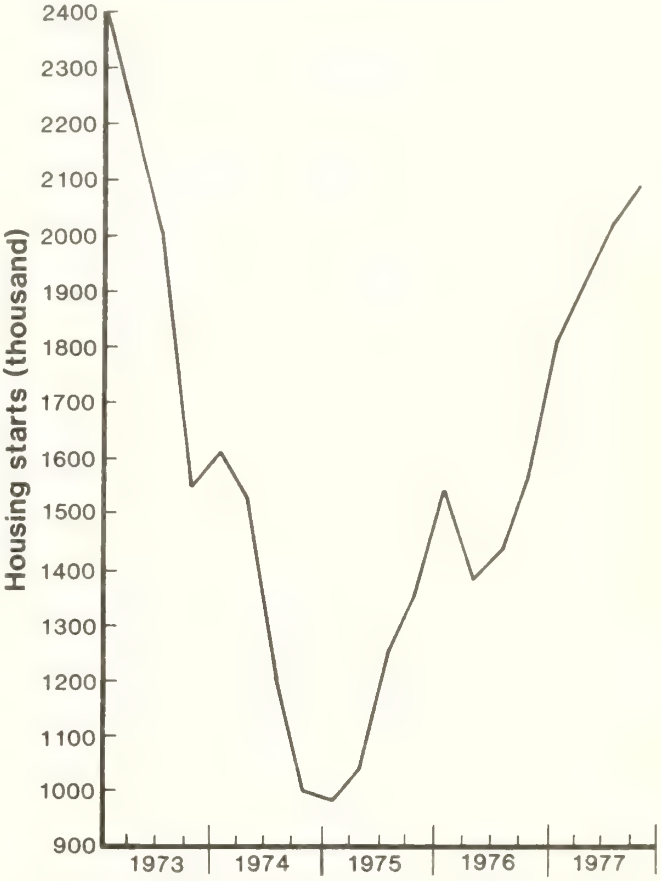

*Figure 4.--Seasonally adjusted, annual housing starts, 1973-77.*

Table 11--Number of employees and annual payroll for manufacturing, lumber and wood products, and total employment--Lewis, Baker, and Union Counties, 1974-77

| Date and industry | Lewis County | | Baker County | | Union County | |
|---|---|---|---|---|---|---|
| | Employees | Payroll | Employees | Payroll | Employees | Payroll |
| | Thousand | Thousand dollars | Thousand | Thousand dollars | Thousand | Thousand dollars |
| 1974: | | | | | | |
| Manufacturing | 4,516 | 45,192 | 702 | 7,251 | 1,488 | 16,593 |
| Lumber and wood products | 3,412 | 35,003 | 486 | 4,892 | 1,219 | 13,976 |
| Total county employment | 11,547 | 96,543 | 2,724 | 19,322 | 4,359 | 33,524 |
| 1975: | | | | | | |
| Manufacturing | 4,554 | 53,413 | 429 | 6,356 | 1,253 | 16,864 |
| Lumber and wood products | 3,062 | 37,465 | 275 | 4,229 | 989 | 14,402 |
| Total county employment | 11,506 | 110,831 | 2,542 | 19,452 | 4,032 | 35,744 |
| 1976: | | | | | | |
| Manufacturing | 4,482 | 62,969 | 555 | 7,953 | 1,437 | 20,794 |
| Lumber and wood products | 3,015 | 45,425 | 393 | 5,483 | 1,193 | 17,877 |
| Total county employment | 11,749 | 128,109 | 2,675 | 24,487 | 4,836 | 46,621 |
| 1977: | | | | | | |
| Manufacturing | 5,009 | 67,766 | 597 | 9,158 | 1,583 | 23,352 |
| Lumber and wood products | 3,649 | 51,556 | 402 | 6,426 | 1,277 | 20,144 |
| Total county employment | 12,976 | 141,265 | 2,859 | 26,570 | 5,056 | 53,425 |

Source: U.S. Department of Commerce (1978a, 1978b).

## National Forest Harvest in the Dependent Communities

Each of these communities depended on National Forest timber to support their forest products industry (Bergvall and others 1977, Howard and Hiserote 1978). The degree of dependency in 1976 was as follows:

| | Lumber | Plywood |
|---|---|---|
| | (Percent) | |
| Lewis County | 42 | 54 |
| Baker County | 75 | 71 |
| Union County | 57 | -- |

### Lewis County, Washington

The semiannual volume of timber sold and cut from the Packwood and Randle Ranger Districts of the Gifford Pinchot National Forest is shown in figure 5. With the drop in volume of timber both sold and cut during 1975-77, the estimated uncut volume of timber under contract remained unchanged over the 1975-77 period (fig. 6).

Uncut inventory on the Packwood Ranger District dropped by 30 million board feet in 1975, although the remaining uncut volume at year end (130 million board feet) was over twice the volume reported harvested from active sales during the year. The uncut volume increased during the first half of 1976, dropped slightly during the third quarter, fell by 10 million board feet during the fourth quarter of 1976 and the first quarter of 1977. The increase in sales activity in late 1977 resulted in an increase of uncut inventory to 159 million board feet by the end of the third quarter of 1977.

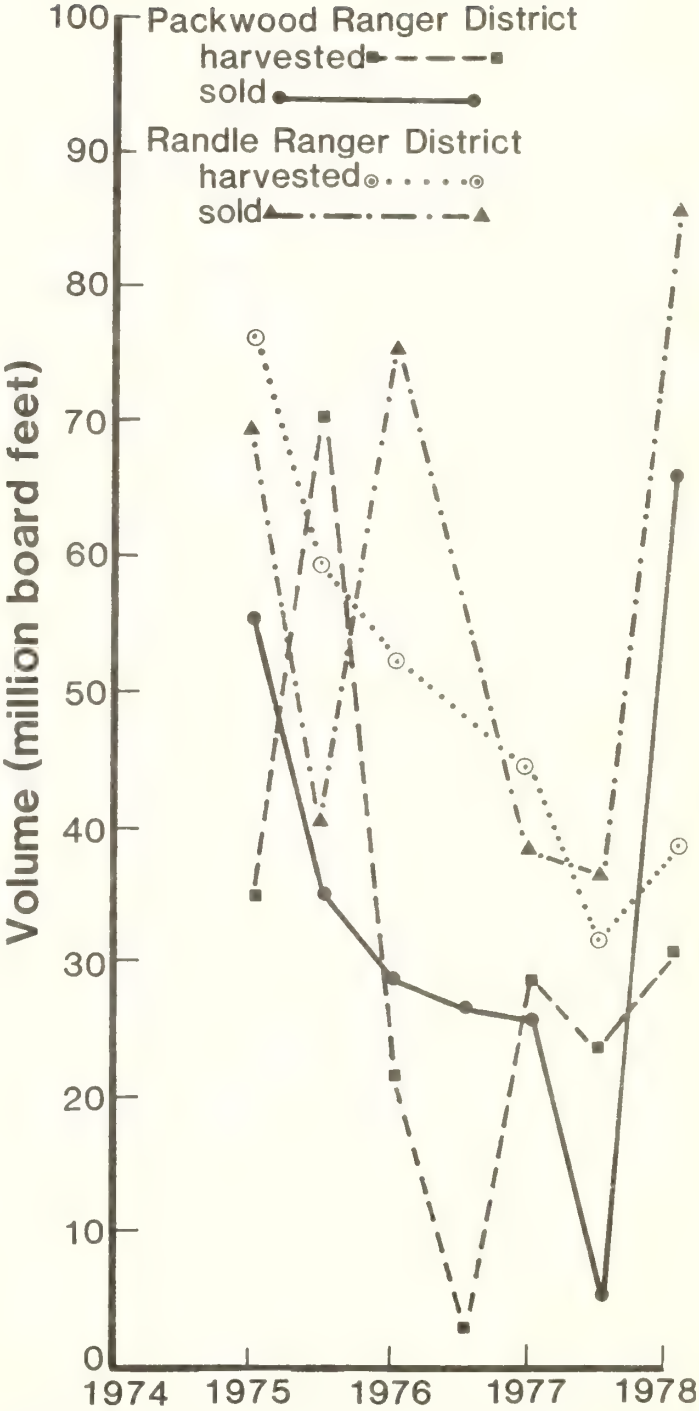

*Figure 5.--Timber harvested and sold semiannually on the Packwood and Randle Ranger Districts, 1975-78.*

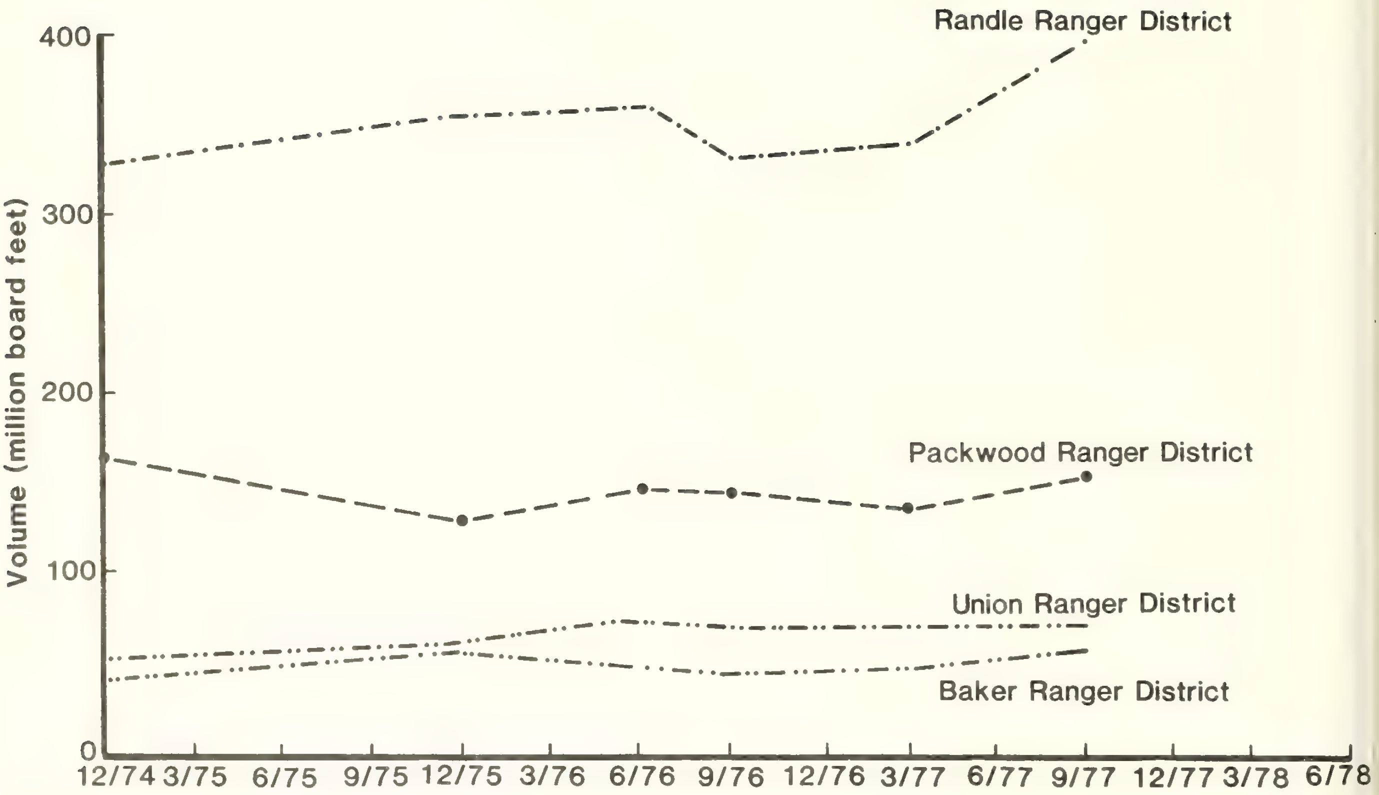

*Figure 6.--Estimated uncut volume of timber by Ranger District, 1975-77.*

Uncut inventory on the Randle Ranger District increased from the beginning of 1975 through mid-1976, at which time the uncut inventory was 364 million board feet. Uncut volume fell during the third quarter to 335 million board feet and then rose sharply to 404 million board feet by the end of the third quarter of 1977. Uncut inventory at the end of 1975 (359 million board feet) was 3.4 times the 1975 cut reported from active sales.

## Baker County, Oregon

Annual volumes sold and harvested for the Baker Ranger District are shown in figure 7, together with the annual allowable cut. Although annual allowable cut was about 34 million board feet, actual sold volume was below the allowable cut in 1973 and 1974. Volume sold was 33 million board feet in 1975 and 14 million in 1976. Sales increased rapidly in 1977, totaling about 42 million board feet. Volume harvested dropped rapidly in 1974 from the high of about 43 million board feet to less than 20 million board feet. Volume harvested declined further in 1975 and then increased in 1976 and 1977, when harvest again exceeded the allowable cut by a slight margin.

Uncut inventory for the Baker Ranger District (fig. 6) increased from about 40 million board feet at the end of 1974 to almost 58 million board feet at the end

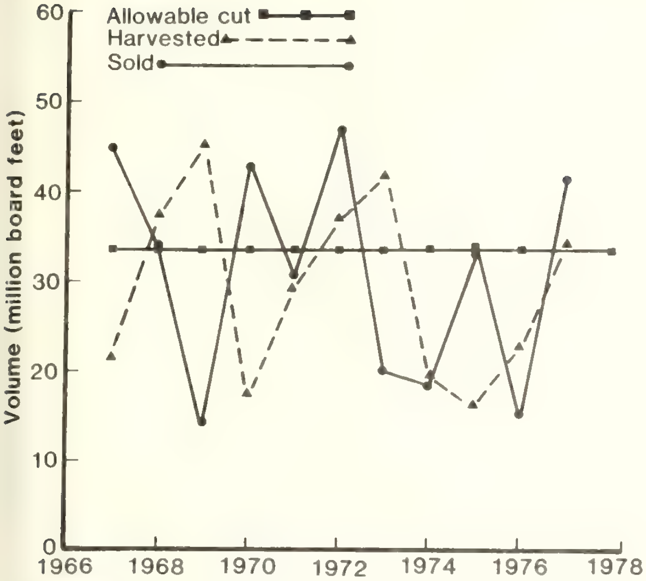

*Figure 7.--Annual volumes of allowable cut that were sold and harvested on the Baker Ranger District, 1967-77.*

of 1975, reflecting the increase in volume sold together with the drop in harvest. Uncut inventory dropped by 10 million board feet during the first three quarters of 1976 and then increased by 12 million board feet by the end of the third quarter of 1977, reflecting the upswing in both sales volume and harvest. Uncut inventory at the end of 1975 was about 1.74 times the reported volume harvested from active sales during the year and 1.7 times the allowable cut. Uncut volume at the end of the third quarter of 1977 was about 1.75 times the allowable cut.

## Union County, Oregon

Annual volumes sold and harvested for the Union Ranger District are shown in figure 8. The pattern in sales is similar to that for the Baker Ranger District, but the downturn in sold volume occurred in 1974 rather than 1973. Likewise, volume sold increased in 1976 from the 1974-75 lows, whereas volume sold did not recover on the Baker Ranger District until 1977. From 1973 through 1977, volume sold exceeded volume harvested, except 1975 when volume harvested exceeded volume sold by a slight amount.

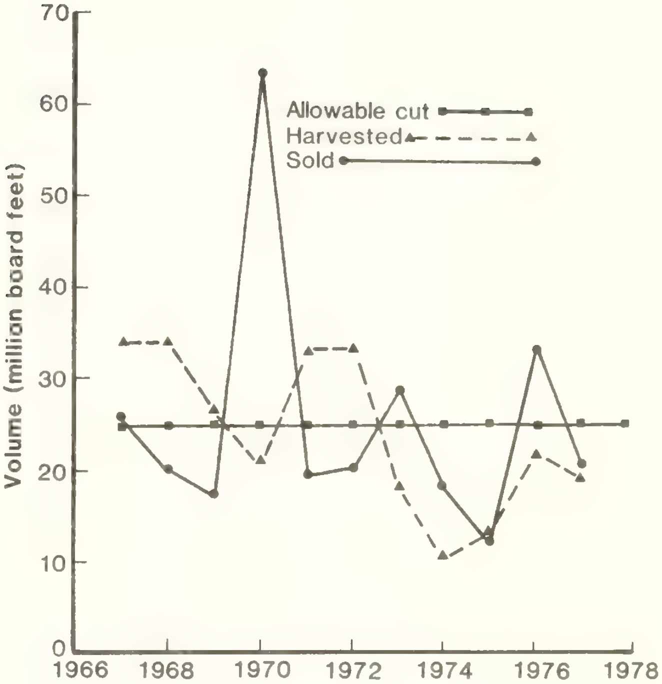

*Figure 8.--Annual volumes of allowable cut that were sold and harvested on the Union Ranger District, 1967-77.*

Uncut inventory under contract (fig. 6) was 50.8 million board feet at the beginning of 1975. With sales volume exceeding harvest in 1976 and 1977, uncut volume increased to 52 million board feet by the end of 1975 and then to 75 million board feet by mid-1976, an increase of 24 million board feet (45 percent) during the first half of 1976. Uncut volume dropped slightly (to 71 million board feet) during the third quarter of 1976 and then increased to 73 million board feet by the end of the third quarter of 1977 as sales volume fell relatively more than the decline in harvest. The uncut inventory was about twice the allowable cut in 1975 and almost 2.9 times the allowable cut at the end of the third quarter 1977.

# The Effect of Uncut Volume on Dependent Communities

One purpose of this study was to examine the role of uncut volumes under contract in timber-dependent communities. This role depends in part on the relationship between timber dependency and community stability. The results of this study support the view that economic market conditions are an important determinant of community stability. The cases examined in this study revealed that the transmission of economic fluctuations at the national level to local economies was responsible for the periods of economic instability during the study period. The absence of adequate markets, rather than timber inventory, contributed to economic instability.

The primary results of this study relate to the nature of timber supply for sustaining forest products manufacturing in the short run. Opponents of sealed bidding often assert that in many areas each timber sale is "critical" to continuance of production by firms in timber-dependent communities. The premise of this concern was that local firms critically in need of a specific timber sale to sustain their operations would "know the competition" and could offer counterbids as necessary to obtain the sale. Another variation on this argument is the possibility that, by knowing the competition, local firms could collectively bid when necessary to protect against timber purchases by "outsiders."

The results indicate that several sales with uncut volumes are held by dominant firms in each of the dependent communities studied. In all cases, a minimum of 3 active sales was held, with the average per period being 26.2 active sales for the Pacific Timber Company, 5.2 for the Ellingson Lumber and Timber Companies, and 4.5 for the Hoff-Ronde Valley Lumber Company. In only two cases (Baker Ranger District in the fourth quarter of 1976 and the first quarter of 1977 and Union Ranger District in 1975) did the harvest exceed the volume purchased when the major purchaser acquired more than 50 percent of the sales sold. In both cases, the previously held uncut inventory exceeded the cut by a factor of at least 2.5 without the additional purchases

As summarized in figure 6, the aggregate uncut inventory at the Ranger District level also does not support the "critical sale" concern. Rather, the patterns of uncut inventory reflect modest response to general economic trends, suggesting that timber inventories are economically determined and that firms balance short-run timber purchase and harvest decisions in response to overall economic conditions

The pattern revealed in this study shows that a decline in both timber harvest and timber sales follows a downturn in general economic activity, with a relatively short lag of 3 to 6 months. During this adjustment interval, harvest and sales will continue at relatively high levels even as product prices soften and fall. During such periods uncut inventory may increase, reflecting the slack in the marketplace. This pattern was evident in the downturn of economic conditions in the slump of 1974 and early 1975.

Conversely, with the recovery in economic activity--as occurred in 1975 and early 1976--business activity increases, prices respond, harvest rates gradually increase, sales volume increases, and uncut inventory may temporarily decline as production accelerates. In spite of the drop in economic activity in 1974 and early 1975 and the rapid turnaround that occurred in 1975 and early 1976, uncut inventories at the District level remained steady and consistently exceeded the level of cut.

# 6. Summary

## Richard W. Haynes

The issue of the impacts of sealed bidding on timber-dependent communities, although quiescent now, is not resolved. The spectre of disruptive bidding raised by opponents to sealed bidding did not materialize during 1977, nor did the choice of bidding method affect the economies of the timber-dependent communities examined in the various case studies. But the 1-year period of sealed bidding may not have been long enough to reflect the effects of sealed bidding on timber-dependent communities.

The lack of a systematic selection scheme for the various case studies diminishes our ability to draw inferences based on statistical validity. There are, however, several general conclusions that can be drawn from the case studies. The first is that the change in bidding method did not lead to significant increases in stumpage prices. The switch did, however, lead to increased activity by outside bidders, and the impacts of outside bidders were generally consistent with what had been assumed. That is, the presence of outside bidders usually led to greater competition and higher prices.

The various case studies indicated that in the short run outside bidders did not impair community stability. This leaves unanswered the question of long-term effects. Would increased prices in the long term increase costs of production to the point that local firms would go out of business with the attendant loss of jobs and indirect adverse impacts on the community?

Another general conclusion was that uncut volume under contract was used as a buffer against short-term changes. In several of the communities, changes in timber flows in any one year were mitigated by the uncut volume from sales obtained in previous years. This suggests that inventories of timber composed of uncut volume under contract and current purchases are managed in response to overall economic conditions. The insurance offered through access to uncut volume under contract is not enjoyed by all firms. Small mills depending on interfirm log transfers and independent loggers both have limited uncut volumes and, as a consequence, bear a disproportionate share of the effects of an economic downturn.

The Grant County case study best illustrates the interrelationships between National Forest harvest flows and county economies. Although this description is indicative of what might exist in other communities, it does point out the fragile nature of the economies of timber-dependent communities where the bulk of jobs, wages, and government services depends on the forest products sector. For example, in Grant County each dollar increase in lumber sales increases local transactions by that dollar plus another $1.55 for a total impact of $2.55. The degree of this dependence has evolved slowly as a function of the comparative advantage of each community.

Concerns for community stability should be oriented toward the causes--economic instability in major markets and the national economy--rather than viewed just in terms of local symptoms. Although adequate timber supply is a necessary prerequisite for production, these analyses indicate that a timber supply constraint, as the limiting factor affecting stability, is not nearly as critical as a healthy national economy.

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Haynes, Richard W., tech. ed. Competition for National Forest timber: effects on timber-dependent communities. Gen. Tech. Rep. PNW-148. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 40 p.

Results are reported for three studies that dealt with the influence of timber sale practices on competition for timber in the timber-dependent communities of Medford and Grant County in Oregon and those surrounding the Nezperce National Forest in Idaho. Results are also reported for a fourth study that examines how several firms managed their uncut volume under contract. Although the description of the various local economies is only indicative of others, these studies point out the fragile nature of the economies of timber-dependent communities where most jobs, wages, and government services depend on the forest products sector.

Keywords: Timber sales, National Forest policy, National Forest administration, stumpage sales arrangements, economic impact.

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General Technical Report PNW-149
February 1983

9

# Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America

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# FOREST CHEMICALS

L.A. NORRIS, H.W. LORZ and S.V. GREGORY

U.S. Department of Agriculture Forest Service
Pacific Northwest Forest and Range Experiment Station

# ABSTRACT

Herbicides, insecticides, fertilizers, and fire retardants are chemicals used to protect or enhance certain forest resources. Their use may directly affect anadromous fish by exposing them to toxic amounts of the chemical. Indirect effects are also possible through chemically induced alteration of habitat, including direct effects on fish-food organisms.

Data on the movement, persistence, and toxicity of chemicals provide a basis for evaluating potential direct effects of chemical use on fish and fish-food organisms. Data are included for seven herbicides (2,4-D, picloram, atrazine, MSMA, fosamine ammonium, glyphosate, and dinoseb), five insecticides (malathion, carbaryl, azinphos-methyl, carbofuran, and acephate), urea fertilizer, and the ammonium-based fire retardants. Comparison of exposures and toxicities of these materials shows their current uses provide a reasonable margin of safety to anadromous fish if direct application to surface waters is avoided.

Much less information is available on indirect effects of chemical use on anadromous fish habitat. The potential effects are known, but few quantitative data exist to evaluate their importance. Apparently, the best way to minimize indirect effects is to minimize the effects of chemicals on all biota in the riparian zone.

Research is needed on the role of buffer strips in reducing entry and impact of forest chemicals in streams, patterns of entry of selected chemicals into streams, instream fate of most forest chemicals, toxicity characteristics of combinations of forest chemicals, the interaction between amount and duration of organism exposure to toxicants, potential latent effects from short-term exposure, effects of forest chemicals on aquatic species under field conditions, and the indirect effects of using forest chemicals on anadromous fish habitat.

KEYWORDS: Anadromous fish, fish habitat, herbicide, insecticide, urea fertilizer, fire retardants, 2,4-D, picloram, atrazine, MSMA, fosamine ammonium, glyphosate, dinoseb, carbaryl, acephate, malathion, azinphos-methyl, carbofuran, ammonia.

USDA FOREST SERVICE
General Technical Report PNW-149

# INFLUENCE OF FOREST AND RANGELAND MANAGEMENT ON ANADROMOUS FISH HABITAT IN WESTERN NORTH AMERICA

William R. Meehan, Technical Editor

## 9. Forest Chemicals

L. A. NORRIS
USDA Forest Service, Pacific Northwest Forest and Range
Experiment Station, Forestry Sciences Laboratory, Corvallis, Oregon

H. W. LORZ
Research and Development Section, Oregon Department of
Fish and Wildlife, Corvallis, Oregon

S. V. GREGORY
USDI Fish and Wildlife Service, Columbia National Fishery Research
Laboratory, Columbia, Missouri, currently at Department of
Fisheries and Wildlife, Oregon State University, Corvallis

1983

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
Forest Service, U.S. Department of Agriculture, Portland, Oregon

# PREFACE

This is one of a series of publications on the influence of forest and rangeland management on anadromous fish habitat in western North America. This paper addresses the effects of forest chemicals on fish habitat. Our intent is to provide managers and users of forests and rangelands with the most complete information available for estimating the consequences of various management alternatives.

In this series of papers, we will summarize published and unpublished reports and data as well as the observations of scientists and resource managers developed over years of experience in the West. These compilations will be valuable to resource managers in planning uses of forest and rangeland resources, and to scientists in planning future research.

Previous publications in this series include:

1. "Habitat requirements of anadromous salmonids," by D. W. Reiser and T. C. Bjornn.
2. "Impacts of natural events," by Douglas N. Swanston.
3. "Timber harvest," by T. W. Chamberlin.
4. "Planning forest roads to protect salmonid habitat," by Carlton S. Yee and Terry D. Roelofs.
6. "Silvicultural treatments," by Fred H. Everest and R. Dennis Harr.
7. "Effects of livestock grazing," by William S. Platts.
8. "Effects of mining," by Susan B. Martin and William S. Platts.
11. "Processing mills and camps," by Donald C. Schmiege.
12. "Rehabilitating and enhancing stream habitat: 1. Review and evaluation," by James D. Hall and Calvin O. Baker.
13. "Rehabilitating and enhancing stream habitat: 2. Field applications," by Gordon H. Reeves and Terry D. Roelofs.

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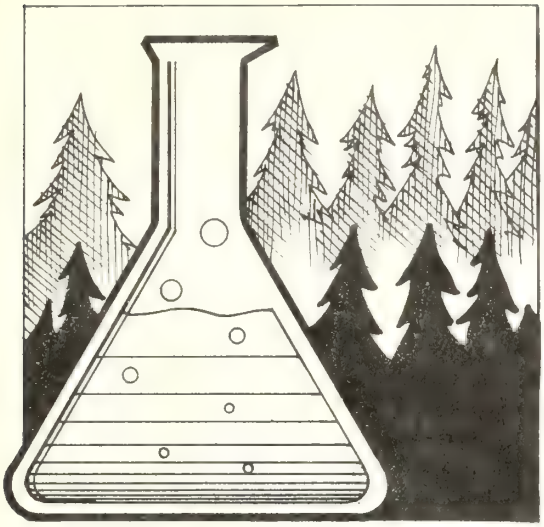

# INTRODUCTION

Forest chemicals are used to protect or enhance a wide array of forest resources. Their use may have adverse effects on anadromous fish or their habitat. Forest managers, regulatory officials, and the interested public believe strongly that if forest chemicals are used, they must yield significant benefits without imposing unreasonably adverse environmental effects. We review and summarize what is known about the interaction between forest chemicals and anadromous fish and their habitat. Our objective is to provide the reader with a scientific basis for making informed, technically sound decisions about the use of these important management tools with respect to anadromous fish and their habitat.

# USE OF CHEMICALS IN THE FOREST

The three major categories of forest chemicals are pesticides,[1] fertilizers, and fire retardants. Many chemicals are used in both agriculture and forestry, but the magnitude, intensity, and patterns of use are markedly different (table 1). The common, chemical, and trade names of forest chemicals used in this paper are in appendix table 18.

Table 1--Comparative annual use of chemicals in agriculture and forestry

| | Agriculture | Forestry |
|---|---|---|
| | $10^3$ kilograms | |
| Pesticides, 1980:[1] | | |
| Insecticides | 138 924 | [2]71 |
| Herbicides | 202 030 | [2]169 |
| Fungicides | 22 700 | [2]9 |
| | $10^3$ metric tons | |
| Fertilizers, 1978:[3] | | |
| Nitrogen | 9 636 | 55 |
| Phosphorus | 2 273 | 5 |

[1] Agricultural data are from table 3, Pesticide Industry Sales and Usage, 1980 market estimates, U.S. Environmental Protection Agency, Washington, D.C., September 1980; forestry data are only for USDA Forest Service, National Forest Systems land, from table E1, Pesticide-Use Advisory Memorandum 284 (2150 Pesticide-Use Management and Coordination, March 12, 1981), USDA Forest Service, Washington, D.C.
[2] USDA Forest Service, National Forest Systems land only.
[3] Bengtson (1979).

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[1] This publication reports research with pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

## PESTICIDES

Pesticides are defined for regulatory purposes as agents used to prevent, destroy, repel, or mitigate pests. The term pesticide includes many specific chemical substances, which can be grouped according to the type of pest they are intended to control: herbicides, insecticides, fungicides, rodenticides, piscicides, and animal repellents. Although many pesticides are registered by the U.S. Environmental Protection Agency (EPA) for use in agriculture, fewer than 10 have substantial use in forestry. Forestry uses account for less than 1 percent of the total pesticides used in the United States.

Herbicides and insecticides account for more than 80 percent of the pesticides used by the USDA Forest Service (table 2). In general, these figures underestimate the total use in forestry because they do not include pesticides applied by other Federal land-managing agencies or by various State and private groups. Fumigants and fungicides account for 10 to 17 percent of the total, but their use is largely restricted to forest nurseries.

The specific herbicides and insecticides used on the National Forests or on other lands through Federal assistance projects coordinated by the USDA Forest Service are listed in tables 3 and 4. 2,4-D and picloram (alone or in combination with other herbicides) accounted for about 70 percent of the herbicides applied in the fiscal years 1979, 1980, and 1981. The use of glyphosate has increased as both registration and use-experience have expanded. The amount of insecticide used was much lower in fiscal year 1981 compared to the two previous years. Malathion, carbaryl, and acephate accounted for nearly all the insecticide used for silvicultural purposes in the fiscal years 1979, 1980, and 1981.

Table 2--Pesticides used by the USDA Forest Service

| Pesticide | Fiscal year 1981[1] | | | Fiscal year 1980[2] | | | Fiscal year 1979[3] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds |
| Herbicides | 197,043 | [6]380,828 | 76.0 | 229,877 | [7]371,748 | 62.1 | 184,048 | [8]471,184 | 63.2 |
| Fumigants and fungicides | 3,618 | 85,363 | 17.0 | 2,375 | 63,015 | 10.5 | 1,334 | 81,265 | 10.9 |
| Insecticides | 49,671 | [9]31,595 | 6.3 | 173,500 | [10]156,590 | 26.2 | 272,420 | [11]173,000 | 23.2 |
| Rodenticides | 51,537 | 1,570 | .3 | 29,693 | 2,063 | .3 | 44,920 | 9,066 | 1.2 |
| Repellents | 6,220 | 1,278 | .2 | 8,998 | 2,723 | .5 | 9,502 | 9,137 | 1.2 |
| Wood preservatives | -- | 255 | <.1 | -- | 1,564 | .3 | [12]-- | [12]-- | [12]-- |
| Piscicides | 92 | 28 | <.1 | 256 | 633 | .1 | 239 | 915 | .1 |
| Algacides | 8 | 353 | <.1 | 17 | 429 | <.1 | 54 | 408 | <.1 |
| Behavioral chemicals | [12]-- | [12]-- | [12]-- | [12]-- | [12]-- | [12]-- | 2,270 | 17 | <.1 |
| Total | 308,012 | 501,271 | 100 | 444,716 | 598,765 | 100 | 514,786 | 744,992 | 100 |
| Percent of 5-year average | 66 | 77 | | 95 | 92 | -- | 110 | 115 | -- |

-- = not applicable, unless otherwise indicated.
Note: The fiscal year begins October 1 of the previous year and runs through September 30 of the year designated.

[1] Pesticide-Use Advisory Memorandum 316 (2150 Pesticide-Use Management and Coordination, April 5, 1982), USDA Forest Service, Washington, D.C.
[2] Pesticide-Use Advisory Memorandum 284 (2150 Pesticide-Use Management and Coordination, March 12, 1981), USDA Forest Service, Washington, D.C.
[3] Pesticide-Use Advisory Memorandum 246 (2140 Pesticide-Use Management, June 5, 1980), USDA Forest Service, Washington, D.C.
[4] 1 acre = 0.4 hectare.
[5] 1 pound = 0.45 kilogram.
[6] 30 percent by aerial application.
[7] 23 percent by aerial application.
[8] 26 percent by aerial application.
[9] 29 percent by aerial application.
[10] 84 percent by aerial application.
[11] 87 percent by aerial application.
[12] No use reported.

Table 3--Herbicides most commonly used by the USDA Forest Service

| Herbicide | Fiscal year 1981[1] | | | Fiscal year 1980[2] | | | Fiscal year 1979[3] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds |
| 2,4-D | 72,587 | 145,474 | 38.2 | 117,174 | 205,676 | 55.3 | 73,449 | 185,323 | 39.3 |
| 2,4-D + picloram | 69,158 | 89,143 | 23.4 | 9,090 | 12,670 | 3.4 | 57,000 | 135,307 | 28.7 |
| Picloram | 15,190 | 33,722 | 8.9 | 68,001 | 35,849 | 9.6 | 15,853 | 24,947 | 5.3 |
| Atrazine | 5,968 | 21,725 | 5.7 | 7,099 | 29,772 | 8.0 | 5,299 | 18,915 | 4.0 |
| Mineral spirits | — | -- | -- | 50 | 15,615 | 4.2 | 89 | 6,600 | 1.4 |
| Glyphosate | 12,489 | 17,622 | 4.6 | 5,667 | 9,601 | 2.6 | 3,668 | 5,841 | 1.2 |
| Dalapon | 4,286 | 12,694 | 3.3 | 4,076 | 9,084 | 2.4 | 4,240 | 10,611 | 2.3 |
| Simazine | 853 | 7,307 | 1.9 | 1,016 | 4,790 | 1.3 | 4,298 | 9,927 | 2.1 |
| Fosamine ammonium | 1,702 | 6,693 | 1.8 | 1,649 | 8,340 | 2.2 | 1,949 | 7,939 | 1.7 |
| Hexazinone | 4,550 | 6,487 | 1.7 | 2,768 | 3,900 | 1.0 | 383 | 839 | .2 |
| Dicamba | 4,208 | 4,786 | 1.3 | 3,714 | 4,207 | 1.1 | 1,060 | 1,404 | .3 |
| 2,4-D + 2,4-DP | 1,142 | 4,180 | 1.1 | 1,777 | 6,877 | 1.8 | 3,152 | 8,947 | 1.9 |
| Sodium metaborate + sodium chlorate | 15 | 2,410 | .6 | 11 | 3,700 | 1.0 | 11 | 793 | .2 |
| Ammonium sulfamate | 260 | 3,000 | .8 | 173 | 1,983 | .5 | 450 | 3,502 | .7 |
| Amitrole | 986 | 2,333 | .6 | 822 | 1,902 | .5 | 880 | 1,710 | .4 |
| MSMA | 940 | 617 | .2 | 1,386 | 421 | .1 | 3,558 | 18,604 | 3.9 |
| 2,4-D + dicamba | 1,612 | 3,421 | .9 | 288 | 164 | <.1 | 6,232 | 14,971 | 3.2 |

-- = no use reported.
Note: The fiscal year begins October 1 of the previous year and runs through September 30 of the year designated.

[1] Pesticide-Use Advisory Memorandum 316 (2150 Pesticide-Use Management and Coordination, April 5, 1982), USDA Forest Service, Washington, D.C.
[2] Pesticide-Use Advisory Memorandum 284 (2150 Pesticide-Use Management and Coordination, March 12, 1981), USDA Forest Service, Washington, D.C.
[3] Pesticide-Use Advisory Memorandum 246 (2140 Pesticide-Use Management, June 5, 1980), USDA Forest Service, Washington, D.C.
[4] 1 acre = 0.4 hectare.
[5] 1 pound = 0.45 kilogram.

Table 4--Insecticides most commonly used by the USDA Forest Service

| Insecticide | Fiscal year 1981[1] | | | Fiscal year 1980[2] | | | Fiscal year 1979[3] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds | Acres[4] | Pounds[5] | Percent of total pounds |
| Azinphos-methyl[6] | -- | 6,431 | 20.3 | -- | 17,923 | 11.4 | — | 4,324 | 2.5 |
| Carbofuran[6] | -- | 5,511 | 17.4 | -- | 4,223 | 2.7 | -- | 5,469 | 3.2 |
| Malathion | 9,601 | 4,854 | 15.3 | 141,485 | 102,347 | 65.3 | 193,364 | 93,512 | 54.1 |
| Carbaryl | 4,984 | 4,521 | 14.3 | 26,091 | 29,687 | 19.0 | 51,178 | 50,508 | 29.2 |
| Acephate | 3,014 | 2,261 | 7.2 | -- | 3 | <.1 | 23,400 | 11,706 | 6.7 |
| Ethylene dibromide[7] | -- | 765 | 2.4 | — | 40 | <.1 | -- | 2,521 | 1.5 |
| Toxaphene[8] | -- | 480 | 1.5 | -- | 1,607 | 1.0 | — | 2,295 | 1.3 |
| Lindane | -- | 163 | .5 | -- | 443 | .3 | 370 | 309 | .2 |
| Diazinon[9] | -- | 162 | .5 | 64 | 81 | <.1 | 101 | 124 | <.1 |
| Tetraclorvinphos[8] | [10] -- | [10] -- | [10] -- | 58 | 54 | <.1 | 31 | 68 | <.1 |

-- = data not applicable, unless otherwise indicated.
Note: The fiscal year begins October 1 of the previous year and runs through September 30 of the year designated.

[1] Pesticide-Use Advisory Memorandum 316 (2150 Pesticide-Use Management and Coordination, April 5, 1982), USDA Forest Service, Washington, D.C.
[2] Pesticide-Use Advisory Memorandum 284 (2150 Pesticide-Use Management and Coordination, March 12, 1981), USDA Forest Service, Washington, D.C.
[3] Pesticide-Use Advisory Memorandum 246 (2140 Pesticide-Use Management, June 5, 1980), USDA Forest Service, Washington, D.C.
[4] 1 acre = 0.4 hectare. Not all applications are per acre; in projects for control of seed and cone insects, for instance, the values in the pesticide-use advisory memorandums are the number of trees treated.
[5] 1 pound = 0.45 kilogram.
[6] Control of seed and cone insects in seed-production areas.
[7] Control of bark beetles on cut logs.
[8] Control of ticks and lice on cattle.
[9] Control of insects in forest-tree nurseries.
[10] No use reported.

## FERTILIZERS

Fertilizers are applied annually to only a small portion of commercial forest land (table 1). Several private and public land-management groups, however, have been applying forest fertilizers for over 10 years, particularly in the Pacific Northwest, where nitrogen deficiencies occur and, to a much lesser degree, in the Southeast, where phosphorous deficiencies may occur. Between 1965 and 1975, about 300 000 ha of Douglas-fir forests were fertilized in western Oregon and Washington (Moore 1975b). Bengtson (1979) wrote an excellent discussion of the use of fertilizers in American forestry.

## FIRE RETARDANTS

The use of chemical fire retardants has increased steadily since they were introduced in the 1930's (table 5). Douglas (1974) and Norris et al.[2] summarized most of the literature on both the use and impacts of chemical fire retardants. Fire retardants are not always thought of as chemical agents, but, in fact, they are. The chemical nature of fire retardants has changed since they were first developed. Borate salts were the first chemical fire retardants to be widely used. They were effective, long-lasting retardants, but were also potent soil sterilants that retarded establishment and regrowth of vegetation. Bentonite clay suspensions in water have also been used, but they are not as effective as other materials. The chemical fire retardants in common use today are composed principally of ammonium phosphate or ammonium sulfate and small amounts of several other chemicals, such as dyes, wetting agents, thickeners, corrosion inhibitors, and bactericides.

Table 5--Fire retardant use in the United States[1]

| Year | Quantity used | User group |
|---|---|---|
| | Liters | |
| 1956 | 87 000 | All users |
| 1961 | 28 400 000 | All users |
| 1966 | 22 500 000 | USDA For. Serv. |
| 1966 | 12 200 000 | Calif. Div. For. |
| 1966 | 3 800 000 | USDI Bur. Land Manage. |
| 1970 | 64 400 000 | All users |
| 1977[2] | 56 669 902 | USDA For. Serv. |
| 1978[2] | 24 371 221 | USDA For. Serv. |
| 1979[2] | 54 795 771 | USDA For. Serv. |
| 1980[2] | 39 348 023 | USDA For. Serv. |
| 1981[2] | 44 712 371 | USDA For. Serv. |

[1] Personal communication, G. E. Cargill, U.S. Department of Agriculture, Forest Service, Washington, D.C. (December 14, 1980 and September 21, 1982 - memorandums with attachments).

[2] Fiscal year. The fiscal year begins October 1 of the previous year and runs through September 30 of the year designated. About 70 percent of this use is in Oregon, Washington, and California.

# RELATION OF USE OF CHEMICALS IN THE FOREST TO ANADROMOUS FISH HABITAT

Water is essential to the habitat of anadromous fish. The quality of the water that forested watersheds yield reflects human activities and natural processes. Forest lands comprise only one-third of the total area of the United States, but they receive more than half of the total precipitation and yield more than three-fourths of the total streamflow. Forested watersheds in the United States on the average receive more than 114 cm of precipitation and yield more than 51 cm of runoff annually, more than seven times the average amount from other lands (Storey 1965). Clearly, the possibility that chemical use in forest management may alter water quality, or some other aspect of anadromous fish habitat, deserves careful consideration.

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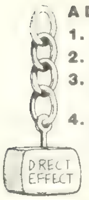
[2] Unpublished report, "The behavior and impact of chemical fire retardants in forest streams," by L. A. Norris, C. L. Hawkes, W. L. Webb, D. G. Moore, W. B. Bollen, and E. Holcombe, U.S. Dep. Agric., For. Serv., Pac. Northwest For. and Range Exp. Stn., For. Sci. Lab., Corvallis, Oreg., 1978.

The chemicals used in forestry may have direct or indirect effects or no effect on anadromous fish. Direct effects require that the organism and the chemical come in physical contact. Once in contact, the chemical must be taken up by the organism and moved to the site of biochemical action where the chemical must be present in an active form at a concentration high enough to cause a biological effect (fig. 1). Direct chemical effects can be evaluated by using traditional concepts of toxicology and dose-response relationships.



**A DIRECT CHEMICAL EFFECT REQUIRES:**

1. DIRECT PHYSICAL CONTACT WITH THE CHEMICAL.
2. UPTAKE BY THE ORGANISM.
3. MOVEMENT TO THE BIOCHEMICAL SITE OF ACTION.
4. RESIDENCE AT THE SITE OF ACTION IN SUFFICIENT QUANTITY AND IN A TOXIC FORM TO CAUSE AN EFFECT.

Figure 1.--A direct chemical effect requires that a chain of events takes place, including direct contact between the organism and the chemical, uptake of the chemical and its movement to the biochemical site of action, and residence at the site of action in an active form, in sufficient quantity and long enough for a direct effect to occur.

Indirect effects result from chemically induced modification of the habitat, rather than from the direct interaction between the chemical and the organism. Examples of indirect effects are insecticide-induced decreases in the biomass of terrestrial or aquatic insects resulting in a decrease in the supply of food for anadromous fish, and reduction in cover, shade, and sources of food from riparian vegetation as a result of herbicide deposition in a streamside zone.

# DIRECT CHEMICAL EFFECTS

One of the hazards of using chemicals in the forest is the risk of direct adverse toxic effects on nontarget organisms. The two factors that determine the degree of hazard are the toxicity of the chemical and the likelihood that nontarget organisms will be exposed to toxic doses. Toxicity alone does not make a chemical hazardous, exposure to a toxic dose must also occur. Therefore, an adequate hazard assessment requires equal consideration of both the likelihood of exposure and the toxicity of the chemical (Norris 1971a, Sanders 1979).

## TOXICITY IN AQUATIC SPECIES

Acute toxicity is the fairly rapid response of organisms to a few, relatively large doses of chemical administered over a short period of time. Chronic toxicity is the slow or delayed response of organisms to many, relatively small doses of chemical administered over a long period of time. The kind of response (acute or chronic) depends on the magnitude of the dose and the duration of exposure.

## EXPOSURE IN THE AQUATIC ENVIRONMENT

Aquatic organisms may come in direct contact with a chemical in water, sediment, or food. The rate and method of application and behavior of the chemical in the environment determine both the level and the length of time any particular chemical will be in one or more of these three compartments.

## Chemicals in Water

Chemicals may enter water by one or more of the following routes: direct application, drift, mobilization in ephemeral stream channels, overland flow, and leaching. Each route of entry results in a different level and duration of entry and, therefore, a different magnitude and duration of exposure. The degree to which any particular route of entry operates depends on the nature of the application, characteristics of the chemical, and characteristics of the area treated.

Many forest chemicals are aerially applied by either fixed- or rotary-wing aircraft, although a large proportion of herbicides are applied by ground-based equipment such as hand-held nozzles fed from either high- or low-pressure pumping systems, backpack sprayers, air-blast sprayers, direct stem-injection equipment, or, occasionally, by scattering of pelletized chemical by hand (table 2). Aerial applications in or near aquatic zones present the greatest probability of introducing chemicals into the aquatic environment by either direct application or drift. Aerial applications away from aquatic zones do not offer any greater opportunity for chemical entry into water than any other type of application. Chemicals that are applied in or near aquatic zones with ground-based equipment can also enter streams by direct application and drift.

Direct application and drift are physical processes that are largely independent of the chemical properties of the material being applied. The principal variables are vertical and horizontal distance between the points of application and the exposed waters, physical characteristics of the material being applied (droplet or pellet size and characteristics of the carrier), atmospheric conditions (wind speed and direction, relative humidity, and temperature), and type of application equipment and its operating parameters. The concepts, principles, and practice of aerial application of pesticides are presented in a series of five papers (by Maksymiuk, Jasumback, McComb, and Witt) in the proceedings of a pesticide applicators' training course (Capizzi and Witt 1971), the proceedings of a workshop on behavior and assessment of pesticide-spray application (Roberts 1976), and a USDA handbook (U.S. Department of Agriculture 1976).

## Direct Application to Surface Waters

Direct application is the route most likely to introduce significant quantities of chemicals into surface waters. It has the potential to produce the highest concentrations and, therefore, cause the most pronounced acute toxic effects. The duration of entry and the subsequent duration of exposure, however, will be brief--a few minutes to a few days (Norris and Moore 1971, Norris 1978). Concentrations that result depend on the rate of application and the ratio of stream-surface area to volume. The persistence of the chemical in the application zone depends on the length of the stream treated, the velocity of streamflow, and the hydrologic characteristics of the stream channel. The concentration of introduced chemicals normally decreases rapidly with downstream movement because of dilution and the interaction of the chemical with various physical and biological components of the stream system.

## Drift From Nearby Spray Areas

Drift from nearby spray areas is similar to direct application except that peak concentrations are lower and the probability of impacts on stream organisms is reduced. Accidental drift of chemical from nearby spray areas to stream surfaces is a likely means of chemical entry into surface waters, but one that can be minimized through careful selection of chemical formulations, carriers, and equipment, and attention to atmospheric and operating conditions.

## Mobilization in Ephemeral Stream Channels

Ephemeral stream channels are difficult to see from the air and may be sprayed along with the rest of the area. The problem may be more acute during aerial applications, because ground applications usually provide greater opportunity for avoiding these areas. Residues remaining in ephemeral stream channels are available for mobilization by the expanding stream system (described by Hewlett and Hibbert 1967) that develops during heavy precipitation. This process probably accounts for increases in chemicals occasionally observed in streams during the first storms after application (Norris 1967, Norris et al. 1978, 1982).

## Overland Flow

Overland flow occurs infrequently on most forest lands because the infiltration capacity of the forest floor and soil is usually far greater than rates of precipitation (Rothacher and Lopushinsky 1974). Bare and heavily compacted soil may yield surface runoff, but these areas are not widespread and would seldom be treated with forest chemicals.

## Leaching

Leaching of chemicals through the soil profile is a process of major public concern, but it is the least likely to occur in forest environments. Most chemicals used in forestry are relatively immobile in soil. Intense leaching can move chemicals a few centimeters to 1 m in depth, but these distances are short in comparison to distances between treated areas and streams (Norris 1971b). Most forest chemicals do not persist long enough for significant leaching to occur.

The various routes of chemical entry into streams result in widely different degrees of exposure to aquatic organisms. Direct application and drift are likely to result in the highest concentrations of chemicals in water, but persistence is brief. Mobilization in ephemeral stream channels and overland flow are associated with periods of significant precipitation, therefore, the concentrations in the water will be substantially less than those resulting from direct applications, although the duration of exposure may be slightly longer. Leaching (if it occurs) can introduce only small amounts of chemical into the stream, although the process could be prolonged.

The degree to which any one of these routes of entry is involved depends on the properties of both the chemical and the environment. Properties of the chemical (such as vapor pressure or solubility in water) and the properties of the environment (such as temperature, moisture, and soil characteristics) interact to produce the particular behavior (movement, persistence, and fate) we observe in the environment (fig. 2). This behavior largely determines the route of entry of chemicals into forest streams.

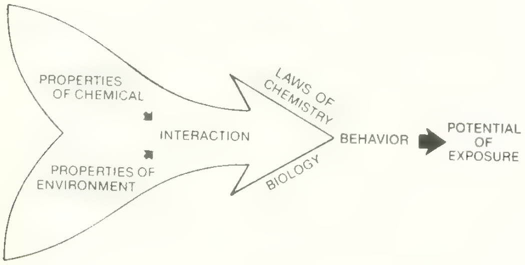


Figure 2.--The properties of the chemical interact with the properties of the environment in a manner directed by the laws of nature to produce the movement, persistence, and fate of the chemical--which determine the level and duration of an organism's exposure.

## Chemicals on Sediment

Stream sediments may be contaminated with forest chemicals by deposition of sediments carrying adsorbed chemicals from the land or by the adsorption of chemical from the water onto sediments already in place in the stream (Barnett et al. 1967).

The deposition of chemically contaminated sediments in streams requires that the chemical be present in the erodible layer of soil at the time erosion occurs. Persistence of the chemical is the predominant factor affecting its presence in the soil. This characteristic will be discussed in more detail in a later section. In general, however, nearly all chemicals are applied between March and October, and surface-erosion events are most frequently associated with intense winter storms from late November through February. Thus, appreciable quantities of a particular chemical must persist for 1 to 9 months for harmful amounts to be present in the soil at the time the first surface-erosion events are likely to occur. Erosion is often accelerated by forest management, but the principal sources of sediment are road construction, road failure, landslides, and streambank erosion (Rice et al. 1972). Chemicals are seldom applied in such a temporal and spatial relationship with these erosion events. We believe significant movement of chemical residues to streams by this process is unlikely. The incidence of surface erosion from forest lands near anadromous fish habitat is discussed in detail in several other papers in this compendium.

Chemicals may be adsorbed from water (see earlier discussion of chemicals in water) by sediments already in the stream. Adsorption of chemical to sediments may be by chemical, physical, or a combination of these types of bonding, as determined by the physical-chemical properties of both the chemical and the sediment. The adsorption process is beyond the scope of our paper. It was reviewed in a series of symposium papers edited by Weber and Matijevic (1968). The adsorption characteristics of forest chemicals are discussed in a later section of this paper.

Norris (1969) and Norris et al. (1982) reported the discharge of pesticides in stream water is believed to represent the mobilization of chemicals in ephemeral stream channels. This research did not distinguish between pesticides in solution and those adsorbed on sediments eroded from the stream channel.

## Chemicals in the Food Chain

Chemicals may be in or on the food of anadromous fish if the food substance is sprayed directly (for instance, if terrestrial insects that are sprayed fall into the water), or if food substances bioaccumulate the chemical from the water. Residues in food from direct spraying are likely to occur primarily during or shortly after application. Few data are available on this process.

Bioaccumulation is the uptake by an organism of a chemical from its environment (for example, the uptake by fish, via the gills, of DDT from the water). Kenaga (1975, 1980a, b) and Geyer et al. (1980) provide good reviews and substantial data on bioaccumulation of organic chemicals, including many pesticides. The physical-chemical properties of the compound and the organism are the predominant factors that determine the extent of bioaccumulation. The most important properties are the level of fat in the organism and the ratio of fat solubility to water solubility of the chemical.

Bioaccumulation resulting in concentrations of chemical in an organism that are 100,000 times the concentration of the chemical in the water have been noted. The highest values occur in organisms with a high fat content that are exposed to chemicals with a high fat solubility/water solubility ratio. DDT or TCDD in fish are pertinent examples. Chemicals that are highly water soluble, like picloram or glyphosate, show little tendency to bioaccumulate. The relation of water solubility to bioaccumulation is illustrated in figure 3, and data for specific chemicals are given in table 6.

Table 6--Water solubility and bioconcentration factor[1]

| Chemical | Water solubility | Bioconcentration factor |
|---|---|---|
| | Milligrams/liter | |
| Acephate | 650 000 | 0.3 |
| Atrazine | 33 | 86 |
| Picloram | 430 | 20 |
| 2,4-D | 900 | 13 |
| Dinoseb | 50 | 68 |
| Carbaryl | 40 | 77 |
| Malathion | 145 | 37 |
| Carbofuran | 415 | 21 |
| Glyphosate | 12 000 | 3 |
| DSMA | 254 000 | .5 |
| Chlordecone | .3 | 333 |
| Mirex | .6 | 820 |
| Methoxychlor | .003 | 16 360 |
| Urea | 1 000 000 | .5 |
| DDT | .002 | 22 500 |

[1] From Kenaga (1980b).

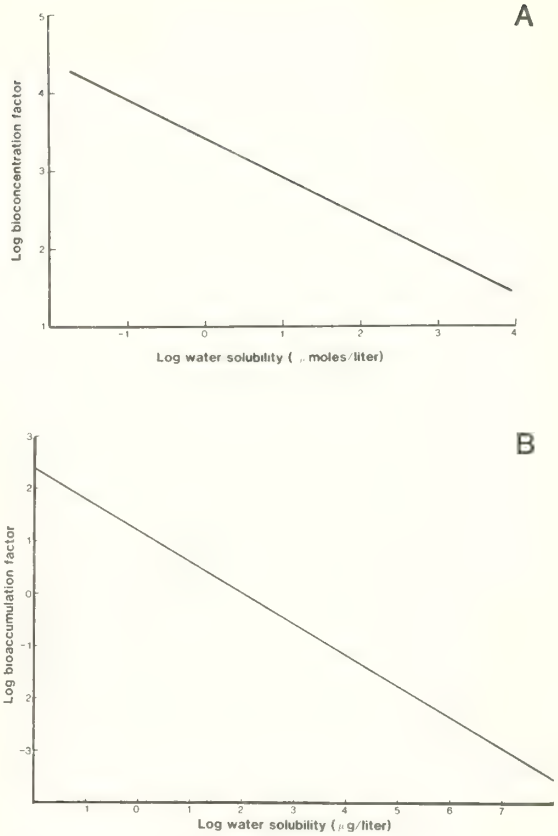


Figure 3.--The relation of water solubility to bioaccumulation.

A. Aqueous solubilities and bioconcentration factors of organic chemicals in rainbow trout. Log bioconcentration factor = 3.41 - 0.508 log water solubility, $r^2 = 0.93$. The bioconcentration factor is the concentration of a chemical in fish divided by its concentration in water (from fig. 2, Chiou et al. 1977).

B. Aqueous solubilities and bioaccumulation in adipose tissue of rats. Log bioaccumulation factor = 1.20 - 0.56 log water solubility, $r^2 = 0.64$. The bioaccumulation factor is the concentration of a chemical in adipose tissue divided by its concentration in the diet (from fig. 1, Geyer et al. 1980).

## APPROACHES TO TOXIC HAZARD ASSESSMENT

Several specific methods have been used to evaluate toxic hazards for aquatic species. Most have used a specified fraction (expressed as a decimal) of the $LC_{50}$ (or similiar measure of response) as an estimate of the no-toxic-effect exposure level (National Academy of Sciences-National Academy of Engineering 1973, U.S. Environmental Protection Agency 1976). This fraction is often called an application factor or safety factor. Where only acute exposures and survival were the primary interest, the estimates of no-toxic-effect level ranged from 0.1 to $0.05(LC_{50})$ (Sprague 1971). For compounds that were more persistent in the environment or when estimates of chronic exposures were desired, the estimate of the no-toxic-effect level ranged from 0.1 to $0.01(LC_{50})$ (Sprague 1971). These methods were popular because the concepts were easy to understand and apply. The methods relied, however, on an assumption that exposure was continuous at the specified level for a long period (usually 96 or more hours). This rationale is perhaps acceptable for large streams receiving a steady input of pollutants or for a specific pollutant point-source, but it does not work well for forest streams where the concentration of pollutant changes rapidly.

A more refined and realistic method has been published (U.S. Environmental Protection Agency 1980) that requires substantial data that define no-effect levels for a variety of aquatic species. In addition, the method provides procedures that give both an instantaneous maximum permissible concentration and a 24-hour average permissible concentration. The EPA procedure is a considerable improvement over earlier methods because it recognizes and allows for variable levels of exposure. It is hampered, however, by a paucity of well-defined, no-effect data bases for many compounds. For the purposes of hazard assessment in this paper, we have selected an approach that combines these two approaches. We have used fractional $LC_{50}$ values as the basis for estimating no-effect concentration values and integrals of the time-concentration curves of pollutants as measured in forest streams to estimate exposure. This approach is described more specifically in a later section on hazard assessment. The next section (the behavior and toxicity of commonly used forest chemicals) provides the data on toxicity and exposure that we use in a later section (hazard assessment) to relate toxicity to exposure and thereby derive estimates of the margin of safety.

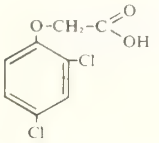
## BEHAVIOR AND TOXICITY OF COMMONLY USED FOREST CHEMICALS

The behavior (movement, persistence, and fate) of a chemical in the environment determines, in large measure, the likelihood and the nature of the exposure organisms will receive. Leonard et al. (1976) made an intensive review of this subject for many pesticides. Although their emphasis was on agriculture, many of the concepts and some of the data are relevant in forestry. In this section, we review what is known about the physical-chemical properties, movement and persistence in soil, entry and fate in forest waters, bioaccumulation, and toxicity to aquatic species of seven herbicides, five insecticides, urea fertilizer, and the ammonium-based fire retardants. These specific materials were selected for review because they are (or are likely to be) the most widely used materials in their class in forestry in the United States. The common and scientific names of organisms mentioned in this paper are in appendix tables 19 (fish) and 20 (invertebrates).

Information on rates and methods of application and carriers for pesticides are in the "Oregon Weed Control Handbook" (Whitesides 1981), the "Oregon Insect Control Handbook" (Capizzi and Fisher 1977), and "Pesticide Uses for Forestry."[3]

# HERBICIDES

## 2,4-D


2,4-D

2,4-D is one member of a large family of phenoxy herbicides which have been reviewed by the National Research Council of Canada (1978) and Norris (1981). The most extensively used herbicide in forestry, 2,4-D is formulated as water-soluble amine salts for direct stem injection or as esters that are usually dissolved in diesel oil or emulsified in water for aerial or ground application to foliage or bark. Rates of application between 1.12 and 4.48 kg/ha are common. More specific information on the use of this herbicide is reviewed by National Forest Products Association (see footnote 3) and Newton (1981).

### Behavior in the Environment

The physical-chemical properties of the acid, salt, and ester forms of 2,4-D are pertinent because the herbicide may be in the environment in any of these forms. It is usually applied as the ester, but is rapidly hydrolized under most circumstances to either the acid or the salt form, depending on the pH of the environment (Paris et al. 1975, National Research Council of Canada 1978, Norris 1981).

The acid of 2,4-D is soluble to about 900 mg/liter at 25 °C in water. The dimethylamine salt of 2,4-D is extremely soluble in water (300 g/100 g) and other polar solvents, such as alcohols and ketones, but it has low solubility in kerosene and diesel oil. Many 2,4-D esters are available; those commonly used in forestry are low in water solubility (less than 500 mg/liter) but are very soluble in organic solvents and oils. The acid and salt forms of 2,4-D have negligible vapor pressure, which means they are not very volatile. The vapor pressure of esters varies from $10^{-2}$ mmHg (high-volatile esters) to $10^{-6}$ mmHg (low-volatile esters).

The methyl, ethyl, propyl, isopropyl, butyl, and amyl esters are called high-volatile esters. They are not used in forestry. Propylene glycol butyl ether (PGBE), isooctyl, butoxyethyl, 2-ethyl hexyl, and propylene glycol esters (and others of similar properties) are called low-volatile esters and are commonly used in forestry. House et al.,[4] National Research Council of Canada (1978), and Weed Science Society of America (1979) review the physical-chemical properties of 2,4-D in more detail.

2,4-D persists in soil for only short periods. Research reviewed by House et al. (see footnote 4) indicates microbial decomposition is the predominant process of 2,4-D disappearance from soil. Environmental factors that favor rapid microbial metabolism also favor the disappearance of 2,4-D from forest floor and soil. Recent research reviewed by National Research Council of Canada (1978) and Norris (1981) support these conclusions.

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[3] Unpublished report, "Pesticide uses for forestry," prepared by Natl. For. Prod. Assoc., Washington, D.C., 1980.

[4] Unpublished final report, "Assessment of ecological effects of extensive or repeated use of herbicides," by W. G. House, L. H. Goodson, H. M. Gadberry, and K. W. Dockter, Contract DAHC 15-68-C-0119, Advanced Res. Proj. Agency, Dep. Defense, Midwest Res. Inst. Proj. 3103-B, Kansas City, Mo., 1967.

In laboratory studies with forest-floor material, Norris (1966, 1970a) and Norris and Greiner (1967) report half lives for 2,4-D that range from 10 to 20 days. In the field, 2,4-D disappeared completely from an oak-forest soil in 30 days (Altom and Stritzke 1972), 90 percent in 31 days in a Minnesota forest,[5] and 40 percent in 15 days from a southern California chaparral site (Plumb et al. 1977).

2,4-D is extensively adsorbed by soil organic matter (Norris 1970b), which tends to reduce its mobility in soil. In light, sandy soils with a high pH, however, it may show substantial mobility (see footnote 4). Forest soils are usually high in organic matter and low in pH, which will inhibit the mobility of 2,4-D. In field studies, 2,4-D residues are not normally found deeper than 20 or 30 cm, even after prolonged periods of heavy precipitation (Altom and Stritzke 1972, Plumb et al. 1977, Stewart and Gaul 1977, Norris et al. 1982, see footnote 5).

Norris (1981) reviewed the entry and fate of 2,4-D (and the other phenoxy herbicides) in forest waters. He concluded direct application and drift to surface waters are the processes most likely to produce the highest residue levels, but the persistence is brief. Mobilization of residues from ephemeral stream channels may also introduce 2,4-D to forest stream systems, but the concentrations are not likely to exceed the concentration resulting from direct application or drift.

Norris (1967) reported maximum concentrations of 2,4-D ranging from 0.001 to 0.13 mg/liter during and shortly after application. The time required to return to nondetectable levels (less than 0.001 mg/liter) varied with the nature of the area and the maximum concentration observed. Times ranging from less than 1 hour to more than 168 hours have been noted, with less than 2 days usually required.

Application to marshy areas can lead to higher than normal levels of stream contamination. In one instance, concentrations approaching 0.9 mg/liter 2,4-D were found in water flowing from a marshy area. Long-term outflow of 2,4-D has not been noted. Once the initial stream concentration declined to nondetectable levels, no 2,4-D residues were found during subsequent periods of heavy precipitation the first fall after application (Norris 1967, 1968). Norris (1969) and Norris et al. (1982) reported heavy precipitation will mobilize any surface residues of 2,4-D that are present in ephemeral stream channels.

Few quantitative studies of 2,4-D discharge for whole watersheds have been conducted. Norris et al. (1982) reported 0.014 percent of the 2,4-D (4.6 kg/ha) applied to a 7-ha watershed appeared in streamflow, all in a 12-day period during the first heavy storm after application (about 4 months after application). Suffling et al. (1974) noted less than 0.001 percent loss of 2,4-D applied to a powerline right-of-way in a similar study.

Results of monitoring operational applications of 2,4-D are largely in agreement with research findings. The U.S. Department of Agriculture, Forest Service,[6] analyzed the results of monitoring phenoxy herbicides in streams after operational application in Pacific Northwest forests. Results of analyses of 680 samples taken in connection with 304 different applications in 4 years were summarized. They reported that of the 304 applications monitored, 84 percent did not result in detectable stream contamination, 14 percent had residues up to 0.005 mg/liter, 1 percent had between 0.005 and 0.01 mg/liter, and 1 percent exceeded 0.01 mg/liter (maximum residue was 0.040 mg/liter).

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[5] Unpublished monitoring report, FY1977 aerial herbicide project, prepared by U.S. Dep. Agric., For. Serv., Chippewa Natl. For., Cass Lake, Minn., 1977.

[6] Memorandum, "Summary of phenoxy herbicides in water," (2150, Pesticide Use Management), from F. J. Kopechky to the Chief, U.S. Dep. Agric., For. Serv., June 23, 1980.

Few field data are available on 2,4-D levels in sediment or aquatic species in forest streams. The fate of 2,4-D in forest streams has not been determined, but we believe downstream movement, adsorption, and degradation (processes observed in other aquatic systems) result in a reduction in both the concentration and total level of 2,4-D in aquatic systems. Gangstad[7] reviewed the fate of 2,4-D in aquatic systems where the herbicide is used to control aquatic weeds. He cited the research of several investigators in noting that the concentration of 2,4-D in hydrosoil or fish flesh did not usually exceed the concentration in water, and disappearance from the system in general was rapid (nearly 100-fold reduction in concentration in 29 days in ponds). Streit (1979) reported 2,4-D was not found on aquatic sediments at concentrations greater than in the water. The sediments in this study ranged from 2.3 to 31.9 percent organic matter. Nesbitt and Watson (1980) noted numerous factors influenced the persistence of 2,4-D in an Australian river. The number of live bacteria, nitrogen and phosphorus concentrations, sediment levels, and temperature were important.

Bioaccumulation is most likely to occur when organisms are exposed to persistent chemicals that have low water solubility and high lipid solubility. 2,4-D does not meet these criteria to the same degree as do the chlorinated hydrocarbon insecticides. Organisms exposed to phenoxy herbicides will take up some of the chemical, but generally the bioaccumulation ratio will be low and the residence time will be brief, once exposure ceases. Böhm and Mueller (1976) reported an accumulation factor of 2.2 for the alga, Scenedesmus, exposed to 0.022 mg/liter for 8 hours. Sanborn (1974) did not detect unmetabolized 2,4-D in the components of an aquatic-terrestrial model ecosystem. Schultz (1973) found less than 0.005 mg/kg 2,4-D in three species of fish exposed to 2,4-D (2.5 mg/liter) for periods of 4, 7, or 14 days, although unspecified metabolic products ranged from 0.031 to 0.122 mg/kg. As part of a widespread survey of the Swedish environment for phenoxy herbicides, Erne (1975) reported only 3 percent of 330 samples of muscles from healthy fish (several species from 120 locations) contained detectable residues of 2,4-D (residues ranged from 0.05 to 1.5 mg/kg). In an aquatic area treated wih 1.2 kg/ha 2,4-D (granule form), mussels contained 0.38 to 0.70 mg/kg 2,4-D, reflecting their consumption of algae that had adsorbed the herbicide. Fish, on the other hand, did not contain detectable residues (less than 0.04 mg/kg) (Smith and Isom 1967). Schultz and Whitney (1974) reported 2,4-D residues that ranged from undetectable to 0.162 mg/kg in a variety of fish species. About 80 percent did not contain detectable residues. A stream gastropod did not concentrate 2,4-D from water (0.0002 to 0.05 mg/liter 2,4-D in water) during a 24-hour exposure period (Streit 1979). Sigmon (1979) reported no measurable residues (less than 0.05 mg/kg) of 2,4-D in bluegills after 8 days in water containing 3 mg/liter 2,4-D (butoxyethyl ester). Rodgers and Stallings (1972) noted 2,4-D and its metabolites were rapidly eliminated from fish after exposure ceased. Extensive data from

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[7] Unpublished draft report, "2,4-D herbicide residues in treated waters," by E. O. Gangstad, U.S. Dep. Agric.-U.S. Dep. Inter., Weed Control Comm., Washington, D.C., 1979.

Ellgehausen et al. (1980) support these findings. The lack of bioaccumulation evident in these results is consistent with the physical-chemical properties of the herbicide.

## Toxicity

A review of the toxicity to fish of 2,4-D herbicides indicates they vary (with 96-hour $LC_{50}$'s ranging from less than 1 mg/liter to more than 400 mg/liter), depending on formulation (National Research Council of Canada 1978). Most studies emphasized lethal concentration of the compounds, carried out by static bioassays; their field applicability is thus somewhat limited. The test animals used in most studies have been bluegills, a species generally considered less sensitive than salmonids.

A review of the toxicity of 2,4-D dimethylamine (DMA) herbicides indicates it is relatively low to fish. Folmar (1976) reported a 96-hour $LC_{50}$ for rainbow trout at 100 mg/liter, but he noted avoidance reaction well below the 96-hour $LC_{50}$ value. Davis and Hughes (1963) and Hughes and Davis (1963) tested the toxicity of different formulations of 2,4-D to bluegills. They found considerable variation in the toxicity of different formulations and even in the toxicity of a single formulation. The researchers believed these inconsistencies could be attributed to the different batch lots and manufacturing plants. The alkanolamine salt and the dimethylamine formulations were the least toxic (800 and 166 mg/liter, respectively, as 48-hour $LC_{50}$, depending on batch) of 11 formulations of 2,4-D tested on bluegills. The isopropyl ester and butyl ester were the most toxic (0.8 and 1.3 mg/liter as 48-hour $LC_{50}$, respectively, for bluegills). These esters are not used in forestry. Davis and Hardcastle (1959) found differences in $LC_{50}$ values for 2,4-D and other herbicides when waters from two different sources were used in toxicity tests.

Walker (1964a) compared toxicity of formulations of 2,4-D to several fish species and found that the butyl, PGBE, and butoxyethanol esters were most toxic (96-hour $LC_{50}$ less than 4 mg/liter), and the sodium salt and isooctyl ester were less toxic ($LC_{50}$ 66 and 160 mg/liter, respectively). He also reported a 96-hour $LC_{50}$ of about 90 mg/liter for a wetting agent (a sodium borate mixture).

In a comprehensive study, Meehan et al. (1974) tested the toxicity of various formulations of 2,4-D to salmonids and found that less than 50 mg/liter 2,4-D acid produced no mortality except in pink salmon fry. The butyl ester, however, was very toxic, causing almost complete mortality in all species at concentrations greater than 1 mg/liter. The isooctyl ester was the least toxic of the ester formulations, but caused significant mortality in fry of several species at 1 and 5 mg/liter. The authors did note, however, that the butyl and PGBE ester formulations of 2,4-D posed a more significant hazard to fish than the isooctyl ester if direct application of the chemical to the water surface occurred. No-effect levels (survival) of the various formulations varied from less than 1 mg acid equivalents (a.e.) per liter for all ester formulations to 50 mg/liter for the acid.

Lorz et al. (1979) observed no mortality of yearling coho salmon exposed to 200 mg/liter of 2,4-D (DMA) for 144 hours, nor did they observe any subsequent effects when these fish were tested in seawater.

Sublethal effects of PGBE esters of 2,4-D have been demonstrated for fish (Cope 1966). Spawning of bluegills was delayed 2 weeks in ponds treated with 5 and 10 mg/liter of the herbicide. Hiltibran (1967) observed that fertilized eggs of green sunfish developed normally when exposed to 1 mg/liter of the PGBE ester of 2,4-D under static water conditions. Bluegills, green sunfish, lake chubsuckers, and smallmouth bass fry, however, appeared to be more susceptible to the herbicide, they failed to survive the 8-day duration of the test.

Woodward[8] found 96-hour $LC_{50}$ values of 0.6 to 1.0 mg/liter with PGBE ester of 2,4-D for cutthroat trout fry. He did not find that toxicity was affected by pH or water hardness. Woodward and Mayer (1978) noted that survival of cutthroat trout alevins was significantly reduced when they were continuously exposed to concentrations of 0.06 and 0.124 mg/liter 2,4-D PGBE ester. The authors suggested that the no-effect concentration for cutthroat trout was 0.03 mg/liter 2,4-D PGBE ester.

Much of the work on fish toxicity of the phenoxy herbicides concerns the PGBE esters of 2,4-D or 2,4,5-T, but little has been done on mixtures of these compounds. Hughes and Davis (1963) found both the 24- and 48-hour $LC_{50}$'s for bluegills exposed to the PGBE ester of 2,4-D were 2.1 mg/liter under static conditions in water with a mean pH of 6.9 and mean hardness of 29 mg/liter. Meehan et al. (1974) observed that the 96-hour no-effect level (survival) for coho salmon fingerlings exposed to the PGBE ester of 2,4-D was less than 1 mg/liter. A mean fry mortality of 26.7 percent occurred after the 96-hour exposure to 1 mg/liter of the herbicide in water that ranged in hardness from 10.0 to 33.6 mg/liter as calcium plus magnesium. A 48-hour $LC_{50}$ of 1.1 mg/liter PGBE ester of 2,4-D was reported by Cope (1966) for rainbow trout (no water quality given). Butler (1965) observed that the 48-hour $LC_{50}$ for the estuarine longnose killifish was 4.5 mg/liter in seawater.

Cope et al. (1970) observed bioconcentration of the PGBE ester of 2,4-D in fish tissues 1 to 3 days after treatment. No detectable residues of the herbicide were found after 4 days in bluegills exposed to 10 mg/liter PGBE ester of 2,4-D. Histological and biochemical changes were also observed in bluegills exposed to 2,4-D (PGBE ester) at and above 5 mg/liter in ponds in Oklahoma (Cope et al. 1970). The pathology involved liver, vascular system, and brain, with depletions of liver glycogen, globular deposits in the blood vessels, and stasis and engorgement of the brain circulatory system.

No deaths occurred in yearling coho salmon exposed to PGBE ester 2,4-D plus 2,4,5-T for 96 hours at equal to or less than 0.800 mg/liter (nominal concentrations, static) or 0.21 mg/liter (nominal concentration in flow-through exposure tanks (Lorz et al. 1979)). In both the static and flow-through systems, the amount of herbicide recovered was very low even though extra care was taken in mixing.

Matida et al. (1975) noted that when a mixture of 2,4-D and 2,4,5-T as the butoxyethanol ester (commercially called "Brush Killer") was aerially spread over 9.5 ha of forest at a rate of 4.05 kg/ha 2,4-D and 1.95 kg/ha 2,4,5-T active ingredient, no appreciable change was noted in the aquatic community. The authors were unable to detect the chemical in the stream during the 48-hour observation period after spraying. Similarly, fishes (cherry salmon and dace (genus not identified) fingerlings) showed no mortality or abnormal behavior, and the standing crop of invertebrates appeared unchanged. In a later laboratory study, Matida et al. (1976) found that a mixture of 2,4-D and 2,4,5-T produced toxic effects on aquatic isopods (Asellus hilgendorffii), cherry salmon fry, and dace fingerlings. The 96-hour $LC_{50}$ for the groups tested were 1.6 (isopod), 0.6 (cherry salmon), and 1.3 (dace) mg/liter. Exposures of cherry salmon fingerlings to concentrations of 0.47 and 0.62 mg/liter "Brush Killer" for 96 hours caused histological changes of liver parenchyma, which the authors considered a nonspecific response to a toxic agent.

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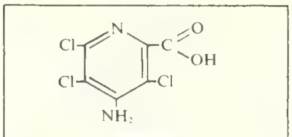
[8] Personal communication, D. Woodward, U.S. Dep. Inter., Fish and Wildl. Serv., Fish-Pestic. Res. Unit, Jackson, Wyo., 1977.

Johnson and Finley (1980) summarized the results of the studies (1965-78) of the USDI Fish and Wildlife Service, Columbia, Missouri, laboratory. They provide a useful table of acute-toxicity values of various formulations of 2,4-D to a variety of invertebrate and fish species.

Sanders (1969) studied the effect of several 2,4-D formulations on the amphipod Gammarus lacustris. The butoxyethanol ester was most toxic--with a 24-hour $LC_{50}$ of 1.4 mg/liter--followed by the PGBE ester (2.1 mg/liter), and the isooctyl ester (6.8 mg/liter). The dimethylamine salt was not toxic at 100 mg/liter (96 hours). In a later study, Sanders (1970) showed the variable toxicity of several 2,4-D formulations to various crustaceans. The PGBE esters were generally most toxic, followed by the butoxyethyl ester formulations. 2,4-D-dimethylamine (DMA) was the least toxic. Crayfish were reported to be less sensitive in this test than Daphnia, seed shrimp, glass shrimp, scuds (amphipods), and sowbugs (isopods). Schultz and Harman (1974) published an excellent review of the literature on the use of 2,4-D in fisheries as it relates to toxicity, residues, and effects on organisms.

## Picloram



**Picloram**

Picloram is a broad-spectrum herbicide used for control of a wide variety of woody annual and perennial broadleaf weeds. It is available in both salt and ester formulations, but the most common used in forestry is either a potassium or amine salt. It is often applied in combination with 2,4-D (Weed Science Society of America 1979). Picloram may be applied as pellets or, more commonly, as a diluted spray mixture. Rates of application range up to 1.12 kg/ha. Picloram may also be used in stem-injection treatments. National Forest Products Association (see footnote 3) and Newton (1981) review uses of picloram in forestry.

### Behavior in the Environment

Amine and potassium salts of picloram are highly water soluble and have negligible vapor pressure (less than $10^{-6}$ mmHg). The physical-chemical properties of picloram are reviewed in detail by the National Research Council of Canada (1974) and the Weed Science Society of America (1979).

Picloram is both persisent and mobile in soil. These characteristics are reviewed in detail by House et al. (see footnote 4), Goring and Hamaker (1971), and National Research Council of Canada (1974). Norris (1970a, b) notes, however, that picloram is adsorbed by organic matter and is degraded by microbial action. In the forest environment, which is characteristically high in organic matter and low in pH, substantially less mobility and persistence have been found than in several agricultural environments.

Movement of the herbicide in the soil profile is governed by the net water flow, with maximum losses occurring under warm, humid conditions, after heavy rainfall, and in light soils that are low in organic content. The removal of picloram through rainfall and leaching is one of the major factors governing its dissipation under field conditions (National Research Council of Canada 1974). This mobility is also of environmental concern, because leached picloram may be transported to aquatic ecosystems. Residues in surface runoff have reached 2 mg/liter after application at 1.1 kg/ha (National Research Council of Canada 1974). Studies have indicated, however, that under most conditions only small proportions of picloram (less than 5 percent) applied to a watershed are transported in surface runoff.

Norris et al. (1976) determined the persistence and leaching characteristics of both picloram and 2,4-D at several sites on power transmission line rights-of-way in Oregon and Washington. Study sites ranged from zones of low to high temperature and rainfall. Both herbicides showed a rapid decline in concentration after application. Biologically significant residues were seldom present more than 12 months after application and no leaching of herbicide below 30 cm was detected (relatively little herbicide was detected below 15 cm). When a forest floor was present, nearly all the herbicide was found in this layer. At another site, Norris et al. (1982) reported picloram and 2,4-D disappeared from soil within 29 months with no significant leaching in the soil profile.

An extensive monitoring effort for picloram and 2,4-D in forest streams flowing across powerline rights-of-way treated with these herbicides failed to show measurable levels of chemicals in streams. In several cases, intensive sampling was done with automatic equipment for periods in excess of 6 months after application (Norris et al. 1976).

Where soil compaction has occurred or where ephemeral streams have been treated, surface residues of picloram may occasionally be mobilized. Norris (1969) reported a maximum concentration of 0.078 mg/liter in surface runoff water from a powerline right-of-way during the first fall rains after application. In a similar situation, Suffling et al. (1974) reported 0.038 mg/liter picloram in runoff the first day after application. In an Arizona watershed study, Johnsen (1980) found a peak concentration of picloram of 0.320 mg/liter in the first flow in an ephemeral stream 157 days after application (2.8 kg/ha to 113 ha of the 146-ha watershed). The concentration decreased with time (less than 0.1 mg/liter after 207 days, less than 0.01 mg/liter after 506 days, last detectable residue at 915 days). A total of 1.1 percent of the picloram applied was discharged in streamflow, 89 percent in the first spring runoff period after application.

In a rangeland setting where picloram was used to control streamside vegetation, residues as high as 0.37 mg/liter were found during the first two storms after application. Subsequent samples did not contain more than 0.05 mg/liter (Davis et al. 1968). Norris et al. (1982) found a similar pattern at a more extensively studied area. In both studies, the concentrations were highest with the first runoff events and decreased rapidly. At one site, 0.35 percent of the picloram applied to a 7-ha watershed was discharged in stream water in the 7 months between the time of application and the time the last sample containing herbicide was collected. All herbicide discharge occurred during the first storms, sufficient to generate streamflow, after application. Suffling et al. (1974) found about 0.22 percent of the picloram applied to a Great Lakes forest opening (a powerline right-of-way) was contained in runoff water in the first year after application.

Only negligible residues of picloram occur in streams in treated areas; apparently the herbicide is rapidly diluted (Haas et al. 1971). Field plots adjacent to a small stream were treated with 1.1 kg/ha of picloram, and water samples were collected 0, 0.8, and 1.6 km downstream from the plots after each rain for 5 months after application. Picloram was detected (0.029 mg/liter) in stream samples only during the first significant runoff. No residues were found in subsequent samples (Haas et al. 1971).

Picloram contamination in lakes has not been reported, but levels in farm ponds adjacent to plots treated with 1.1 kg/ha picloram reached 1 mg/liter (National Research Council of Canada 1974). Dissipation of the herbicide in ponds appears to be rapid. One study found an initial decline of 14 to 18 percent of the picloram per day, followed by a decline of less than 1 percent per day 15 weeks after application (Haas et al. 1971). Residues of picloram (148 μg/kg) in pond sediments immediately after application were only twice that in the water, according to Kenaga (1973, as cited in National Research Council of Canada 1974). After 75 days, 7 μg/kg picloram was detected in the pond sediments and 0.1 μg/kg picloram was found in the water. Dennis et al. (1977) measured picloram residues in water and sediment from ponds and streams after extensive use of picloram for control of woody vegetation on pastures in West Virginia. Picloram residues reached higher levels in water in ponds (up to 0.437 mg/liter) than in streams (up to 0.011 mg/liter), although the levels generally decreased with both time and distance from the treated area. Generally, residues were higher in the water than in the sediment in both streams and ponds. No picloram was detected in stream sediments despite concentrations in water that ranged from nondetectable to 0.011 mg/liter.

Johnsen and Warskow (1980) injected picloram and 2,4-D into a small stream (stream-discharge volume was 0.036 $m^3$/second) for 50 minutes to achieve a concentration of 6.26 mg/liter picloram. The highest concentration outside the treatment zone was 2.4 mg/liter at the first sampling station, 0.4 km downstream. Peak concentrations at other downstream locations were 0.94 mg/liter at 0.8 km; 0.32 mg/liter at 1.6 km; 0.014 mg/liter at 3.2 km; and 0.001 mg/liter at 6.4 km. The herbicide was not detected after 2 days. Stream water, originally containing 1.280 mg/liter picloram, contained only 0.544 mg/liter (a 57-percent reduction) after exposure to direct sunlight for 8.8 hours.

The physical-chemical properties of picloram are not compatible with extensive bioaccumulation. The high water solubility of picloram and its low lipid solubility suggest it will be rapidly excreted as exposure decreases. Residue analyses of aquatic organisms exposed to picloram indicate that this herbicide is not bioconcentrated in invertebrates or other food-chain organisms (National Research Council of Canada 1974). Daphnia exposed to 1 mg/liter of the potassium salt of picloram had whole-body residues of the herbicides equal to that present in the water (Hardy 1966). Bioconcentration of picloram (acid) was not evident in mosquitofish exposed to 1 mg/liter (a.e.) for 18 days (Youngson and Meikle 1972, as cited in National Research Council of Canada 1974). The concentration factor for these fish on a wet-weight, whole-body basis was only 0.02. The 18-day exposure to picloram was adequate to achieve a steady-state level of accumulation in the mosquitofish. Kenaga (1980a) reported a bioconcentration factor of 31 in a flowing water system compared to a factor of 0.02 in a static system.

## Toxicity

The toxicity of picloram to fish is influenced by its formulation and the quality of the water (Sergeant et al. 1970, Woodward 1976). Technical-grade picloram (active ingredient 90 percent) was found to be more toxic under alkaline conditions (Woodward 1976) than under nonalkaline conditions. Increasing the pH from 6.5 to 8.5 increased the toxicity to cutthroat and lake trout by a factor of 2 in both species. Increasing temperature led to an increase in toxicity, but increasing hardness did not (Woodward 1976).

The acute toxicity of picloram varies considerably with the formulation and fish species. The isooctyl ester of picloram appears to be the most toxic commercial formulation (Kenaga 1969, Sergeant et al. 1970, National Research Council of Canada 1974). $LC_{50}$'s reported for this formulation are about 1 mg/liter for sensitive species. Tordon 22K (potassium salt) is considerably less toxic to several fish species (table 7).

Table 7--Mortality data for several fish species exposed to Tordon 22K for 96 hours[1]

| Fish species | Water temperature | Concentration (acid equivalents) | Mortality[2] |
|---|---|---|---|
| | Degrees C | Milligrams/liter | Percent |
| Black bullhead | 10 | 91 | 50 |
| | 10 | 69 | 0 |
| Bluegill | 18 | 5.4 | 50 |
| Brook trout | 10 | 91 | 50 |
| | 10 | 69 | 0 |
| Brown trout | 10 | 52 | 50 |
| | 10 | 22 | 0 |
| Fathead minnow | 10 | 29 | 50 |
| | 10 | 22 | 0 |
| Green sunfish | 10 | 91 | 50 |
| | 10 | 39 | 0 |
| Lake emerald shiner | 21-26 | 30 | 50 |
| Rainbow trout | 10 | 58 | 50 |
| | 10 | 22 | 0 |

[1] Modified from Kenaga (1969).

[2] 50-percent mortality indicates the calculated or derived 96-hour $LC_{50}$ values; 0-percent mortality indicates the highest concentration producing no mortality.

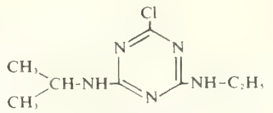
Green sunfish exposed to the 99-percent analytical-grade picloram (1.2 mg/liter a.e.) were not affected, but the technical-grade or the 22-percent commercial formulation of picloram (for up to 1 hour) caused immobilization but not death (Sergeant et al. 1970). Recovery of normal swimming response followed transfer to clean pond water. Two subsequent exposures to the herbicide shortened the recovery times; after a fourth exposure, however, many of the fish failed to recover. Analytical-grade picloram did not affect swimming behavior of green sunfish. Sergeant and coworkers suggested that technical-grade and commercial formulations of picloram might contain a toxic impurity.

Based on available information, chronic picloram toxicity to fish is not cumulative in terms of lethality (National Research Council of Canada 1974, Woodward 1976). Long-term exposures, however, have been shown to affect fish development and growth (Woodward 1976) and swimming response and liver histopathology (Sergeant et al. 1970). Woodward (1976) observed that the no-effect concentration of technical-grade picloram for lake trout was apparently less than 0.035 mg/liter, because this level of herbicide reduced fry survival and growth. Most mortalities occurred during yolk absorption, which took 4 to 5 days longer in picloram-treated fish.

In a long-term experiment (10 weeks), Hardy (1966) found that growth and reproduction of Daphnia were unaffected by 1.0 mg/liter of picloram. Lynn (1965) reported that Daphnia survived a 24-hour exposure to 380 mg/liter of Tordon 101, but 95 percent were killed at a concentration of 530 mg/liter. Sanders and Cope (1968) found the 24-hour $LC_{50}$ for stonefly nymphs (Pteronarcys californica) exposed to picloram (technical, emulsifiable concentrate) was 120 mg/liter, but the 96-hour $LC_{50}$ was 48 mg/liter. Johnson and Finley (1980), using picloram (technical material 90 to 100 percent), give the 96-hour $LC_{50}$ of Gammarus fasciatus and Pteronarcys (2d-year class) as 0.027 and 0.048 mg/liter, respectively.

Lorz et al. (1979) estimated the 24-hour $LC_{50}$ of Tordon 22K and Tordon 101 (a 4:1 mixture of 2,4-D:picloram) as 17.5 and 20 mg/liter, respectively, for yearling coho salmon. When the survivors were challenged with seawater, some of the groups that had received the lowest herbicide concentration suffered mortalities to 70 percent. Reasons for the deaths in seawater after low herbicide exposure are unknown. When coho salmon yearlings were exposed for 96 and 360 hours to Tordon 101 and then released into a small coastal stream, their downstream movement was generally inhibited except for the groups receiving the lowest concentration (0.3 mg/liter). In well-planned spray operations in forestry, similar concentrations (those that might cause inhibition of migration) are unlikely to occur in streams.

## Atrazine



Atrazine

Atrazine is one of a large group of compounds called triazine herbicides. It is widely used as a selective herbicide for control of broadleaf and grassy weeds in both agriculture and forestry at rates up to 4.48 kg/ha. At higher rates of application, it can be used for nonselective control of vegetation on noncroplands. National Forest Products Association (see footnote 3) and Newton (1981) reviewed the use of atrazine in forestry. An extensive review of the triazine herbicides is included in a special volume of "Residue Reviews" (Gunther and Gunther 1970).

### Behavior in the Environment

Atrazine has fairly low solubility in water (33 mg/liter) with substantial solubility in several organic solvents (chloroform, 52 000 mg/liter; methanol, 18 000 mg/liter; diethyl ether, 12 000 mg/liter). Although its vapor pressure is low ($3x10^{-7}$ mmHg), it is reported to volatilize from both vegetation and soil surfaces (Kearney et al. 1964, Burt 1974).

At normal rates of application, most of the atrazine disappears within a year of application. Axe et al. (1969) found only 33 percent of the atrazine remained in soil 5 days after application. Birk and Roadhouse (1964) reported 90-percent loss of atrazine within 1 year in agricultural soils. In the same study, they found 85 percent of the atrazine was in the top 2.5-cm layer of soil and 5.7 percent in the 2.5- to 5.0-cm soil layer after 21 cm of rain had fallen. Marriage et al. (1975) reported no significant accumulation of atrazine even after annual applications of 4.5 kg/ha in nine consecutive years.

Measurable residues of atrazine were confined to the upper 15 cm of the soil profile, with the vast majority of the herbicide in the 0- to 5-cm soil layer.

Atrazine losses in runoff water and soil sediment have been measured on agricultural lands. Hall et al. (1972) reported atrazine losses in runoff ranging from 0.01 to 5.0 percent of the applied atrazine within the first season after application. About 90 percent of the loss occurred within the 1st month after application. The magnitude, frequency, and intensity of precipitation were important factors in determining the amount of atrazine in runoff. Runoff of water in this study ranged from 17 to 68 percent of the incident precipitation, resulting in loss of as much as 10 000 kg of soil/ha (silty clay loam soil, 14-percent slope). In two small (1.3- and 1.4-ha) agricultural watersheds in Georgia, 0.2 and 1.9 percent of the atrazine applied were recovered in storm-generated runoff during the first 90 days after application (1.45 and 4.03 kg/ha). The first runoff events were 6 and 24 days after application. Most of the atrazine recovered (83 and 99 percent) was in solution (Leonard et al. 1979).

Frank and Sirons (1979) monitored streams in 11 agricultural watersheds (average size 4279 ha) for atrazine in both water and sediment. The herbicide or its metabolites were found in 80 percent of the streams with a mean concentration of 0.0014 mg/liter. Peak concentration did not exceed 0.032 mg/liter. About 62 percent of the atrazine discharge was associated with storm runoff, 21 percent in base flow, and an additional 22 percent as the result of chemical spills. Atrazine was detected in stream-bottom sediments in 4 of 10 sets of samples (concentrations ranged from not detected to 20 mg/kg).

Smith et al. (1975) analyzed water samples from irrigation ditches and basins that had been sprayed with atrazine when ditches were dry. After the ditches had been filled twice, no residues of atrazine were detected in the water. These results indicate mobilization of atrazine in ephemeral stream channels is most likely to be restricted to the first few significant storms after application. Weidner (1974) noted a significant degree of atrazine degradation in ground water, although the rate of degradation was slower than would be expected for the same herbicide in soil. Maier-Bode (1972) reported that initial concentrations of atrazine of 0.5 mg/liter in water decreased by 90 percent within 2 weeks and 99 percent within 8 weeks in experimental fish ponds. Herbicide concentrations in the sediment 4 days and 8 weeks after application were 180 percent and 50 percent of the respective initial concentrations in water. Newton[9/] collected water samples from a small stream draining a Christmas tree plantation; he reported atrazine residues in water ranging from 0.42 mg/liter 10 minutes after application (3.0 kg/ha) to 0.02 mg/liter 17 days later. Heavy rain 3 days after application increased the concentration to 0.21 mg/liter on the 4th day, but it had decreased to 0.04 mg/liter by the next day, presumably reflecting decreased loading of silt with adsorbed atrazine.

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[9/] Personal communication, M. Newton, For. Res. Lab., Corvallis, Oreg., 1967.

Based on its physical-chemical properties, atrazine would be expected to show little tendency for bioaccumulation. Böhm and Mueller (1976) noted that increasing water solubility of the herbicide resulted in a decrease in the absolute level of the herbicide in algae. The accumulation factor was 31.8. After a transfer of contaminated algae into an atrazine-free medium, the herbicide was rapidly desorbed, except for about 10 percent of the residue, which was apparently bound irreversibly to cell structures. Streit (1979) reported concentration factors ranging from less than 1 to 8 in some body parts of a stream gastropod exposed to 0.5 mg/liter atrazine for 24 hours. Paris et al. (1975) reported no measurable adsorption of atrazine by dense populations of microorganisms in aquatic cultures. Ellgehausen et al. (1980) studied the bioaccumulation, depuration, and bioconcentration of atrazine by algae, daphnids, and catfish. They reported bioaccumulation factors of about 90, 1, and 5; depuration halftimes of 0.03 hour, 9.5 hours, and 1.5 days; and biomagnification factors of less than 10. The intensive study reported by these authors indicates no significant bioaccumulation of atrazine will occur in aquatic environments in the forest. A mollusk accumulated atrazine to a level 3 to 4 times greater than the concentration in water (0.05 mg/liter) during a 72-hour exposure period. Most of the accumulation occurred in the first 12 hours. Similar results were obtained with whitefish. Water rather than food appeared to be the major source of the herbicide (Gunkel and Streit 1980).

Douglass et al. (1969) found a peak concentration of atrazine in stream water of 0.03 mg/liter shortly after application (4 kg/ha) and during the first periods of heavy precipitation. After this time, residues did not exceed 0.010 mg/liter (the minimum quantifiable concentration). In a second application (3.36 kg/ha 2,4-D plus 5 kg/ha atrazine), an unsprayed 3-m buffer strip was left adjacent to the stream. No residues of either herbicide were detected in the water. In one test, atrazine concentrations were about 40 times higher on sediments than in water, although the concentration on the sediment seemed independent of the organic-matter content over a range from 2.3 to 31.9 percent (Streit 1979).

## Toxicity

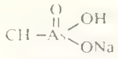
Laboratory and field tests have indicated that atrazine is moderately toxic to fish compared with other herbicides. Macek et al. (1976) investigated the effects of atrazine on survival, growth, and reproduction of three species of fish. Using soft water (hardness 33 to 40 mg/liter) and a continuous-flow apparatus, Macek et al. (1976) were able to show in acute toxicity tests that both the 96-hour and incipient $LC_{50}$ for fathead minnows were 15 mg/liter atrazine. The acute 96-hour $LC_{50}$ for bluegills was more than 8.0 mg/liter and the incipient $LC_{50}$ was 6.7 mg/liter (5.4 to 8.4), which agrees with the 96-hour $LC_{50}$ of about 6 mg/liter atrazine (wettable powder) reported by Walker (1964b) for this species. The 96-hour $LC_{50}$ for atrazine toxicity to brook trout reported by Macek et al. (1976) was 6.3 mg/liter (4.1 to 9.7) and the incipient $LC_{50}$ was 4.9 mg/liter (4.0 to 6.0).

Lorz et al. (1979) found that yearling coho salmon exposed for 144 hours to 15 mg/liter atrazine suffered only a 25-percent mortality. When the survivors of the bioassay were challenged with seawater, only the two groups that had received the highest atrazine concentration suffered any additional mortality.

Spawning, survival, and growth of bluegills and fathead minnows were not affected by exposure to 0.095 and 0.213 mg/liter atrazine, respectively (Macek et al. 1976). Hiltibran (1967) found that 10 mg/liter granular atrazine did not affect embryo development of green sunfish, or survival of bluegills and green sunfish during 8 days. Lake chubsucker fry survived 10 mg/liter wettable powder atrazine. Similarly, parental survival, egg production, and hatchability of brook trout appeared to be unaffected by exposure to 0.72 mg/liter atrazine (Macek et al. 1976). Survival and growth of brook trout fry were, however, significantly reduced after 90 days of exposure to 0.72, 0.45, and 0.24 mg/liter atrazine. Analysis of muscle tissue from bluegills, fathead minnows, and brook trout indicated that these fish did not bioconcentrate detectable amounts of atrazine (detection limits ranged from 0.2 to 1.7 mg/kg) after prolonged exposure (bluegills exposed to 0.094 mg/liter for 78 weeks, brook trout exposed to 0.74 mg/liter for 44 weeks, and fathead minnows exposed to 0.21 mg/liter for 43 weeks) (Macek et al. 1976).

Walker (1964b) observed no fish mortality after application of 2.0 to 6.0 mg/liter atrazine to ponds infested by aquatic weeds. He suggested, however, that atrazine could affect fish in ways other than direct toxicity. A reduction in bottom fauna was observed immediately after application. Among the most sensitive were mayflies (Ephemeroptera), caddisflies (Trichoptera), leeches (Hirudinea), and gastropods (*Musculium*). Studies by Macek et al. (1976) on the chronic toxicity of atrazine to selected aquatic invertebrates indicated that morphological development of progeny is particularly sensitive. Exposure of two successive generations of chironomids to 0.23 mg/liter atrazine resulted in reduced hatching success, larval mortality, developmental retardation, and a reduction in the percentage of pupating larvae and emerging adults. Continuous exposure to 0.25 mg/liter atrazine significantly reduced production of *Daphnia magna*. Development to the seventh instar of the $F_1$ generation of gammarids exposed to 0.14 mg/liter atrazine was reduced 25 percent below that of lower concentrations and controls.

# MSMA



$\mathrm{CH_3{-}\overset{\overset{O}{\|}}{As}\!<^{OH}_{ONa}}$

MSMA

MSMA is a pentavalent organic arsenical herbicide. In forestry, its principal use has been stem injection, both for precommercial thinning and to aid in control of certain bark beetles. These particular patterns of use provide only limited opportunity for entry into the aquatic environment. National Forest Products Association (see footnote 3) and Newton (1981) reviewed the use of MSMA in forestry. Norris[10/] reported the results of a major study of the behavior and impact of the organic arsenical herbicides in the forest environment.

## Behavior in the Environment

The water solubility of MSMA is 25 g/100 g of water at 20 °C. Although it has very little vapor pressure, MSMA may be altered by microbial action to derivatives of arsine that are volatile. The behavior of MSMA in the environment was reviewed by Ray (1975). In soils, MSMA reacts with iron, aluminum, calcium, and magnesium to form compounds of low solubility. Wauchope (1975) reported the organic arsenicals are intensively adsorbed by soils with high contents of clay, iron, and aluminum oxide. The phytotoxicity of MSMA is rapidly dissipated in soil, probably through a strong interaction between the herbicide and soil particles. Some microbial degradation of MSMA has been reported; an arsenate was the product of the metabolism (Von Endt et al. 1968). Robinson (1975) measured arsenic residues in soils over a 5-year period after annual applications of MSMA at rates ranging from 4.4 through 288 kg/ha. Elemental arsenic did not increase in any plot receiving MSMA at rates less than 36 kg/ha. The mechanisms of loss in these studies were not determined.

Dickens and Hiltbold (1967) conducted column leaching studies that showed that after 20 successive 2.5-cm increments of water were added to a loam sand, about half of the applied MSMA remained in the surface 2.5 cm of soil and none was leached below 15 cm. Using columns of forest-floor material and soil from ponderosa pine, Douglas-fir, and mixed-fir forest types, Norris (see footnote 10) determined MSMA was rapidly leached through the forest-floor material but was not leached in the three different soils by 86.4 cm of water applied over a 20-day period. In tests with 2.54 cm of undisturbed forest-floor material, as little as 2.5 cm of water delivered over an 8-day period was sufficient to move about half of the surface-applied MSMA through the forest-floor material. These results indicate that MSMA deposited on the forest floor will readily move through it to the soil--even with small amounts of precipitation. Once reaching the soil, however, MSMA is rapidly immobilized.

Norris (see footnote 10), reporting the work of Canutt and Norris, observed a decline with time in the arsenic concentration in the forest floor under stands that had been precommercially thinned with MSMA. The fate of arsenic in the forest floor was not determined, but the small increases in soil residues indicated some movement from forest floor to soil.

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[10/] Unpublished report, "The behavior and impact of organic arsenical herbicides in the forest: final report on cooperative studies," by L. A. Norris, U.S. Dep. Agric., For. Serv., Pac. Northwest For. and Range Exp. Stn., For. Sci. Lab., Corvallis, Oreg., 1974.

Norris (see footnote 10) looked for arsenic in four different streams flowing from areas that had been precommercially thinned with MSMA. Samples were collected at various intervals after treatment, with special emphasis given to storm periods when runoff events might occur and again during spring runoff. Only five samples contained detectable quantities of arsenic; four of these five were at the minimum level of detection; the fifth sample was from an upstream site presumably containing water that had not passed through areas previously thinned with MSMA. The results of this study indicate the careful application of MSMA in thinning programs poses little or no threat of increased arsenic levels in aquatic systems.

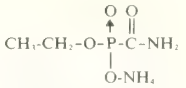
Woolson et al. (1976) determined the distribution and persistence of MSMA in two aquatic model ecosystems. One system contained sandy loam soil as the sediment, channel catfish, and crayfish; the second system contained sediment, algae, daphnids, *Gambusia*, and crayfish. The concentration of arsenic in the water was reduced from 2 to 10 times in 5 days. Catfish showed little tendency to bioaccumulate arsenic from MSMA (bioaccumulation ratio of 4:1) and showed substantial reduction in bioaccumulation level after 14 days in fresh water. Crayfish (*Procambarus clarki*) showed higher levels of accumulation (bioaccumulation ratios of 80:1 to 480:1). They also showed a 50-percent decrease in arsenic concentration after 18 days in fresh water. The second experiment was conducted similarly, and different results were obtained. *Gambusia* had bioaccumulation ratios of about 100:1, but crayfish showed bioaccumulation ratios of less than 10:1. Daphnids and algae had bioaccumulation ratios of 5:1 and 34:1, respectively. Although MSMA does show a slight tendency for bioaccumulation, the limited probability that it will be present in aquatic systems in the forest reduces the importance of this characteristic.

## Toxicity

Only limited data are available on toxicity effects of MSMA to fish. The 96-hour $LC_{50}$ ranges from 12 to more than 100 mg/liter, depending on species, test conditions, and the amount of active ingredient in the formulation tested (U.S. Environmental Protection Agency 1975, Johnson and Finley 1980). McCorkle et al. (1977) found less than 10-percent mortality occurred in fingerling channel catfish held for 48 hours under static conditions at 10 mg/liter of MSMA.

Sanders (1970) found that MSMA was not toxic to the scud (*Gammarus fasciatus*) after 96 hours of exposure at 100 mg/liter. Spehar et al. (1980) recently completed experiments on the comparative toxicity of arsenic compounds and their accumulation in invertebrates and fish. These investigators noted that concentration of 1 mg As/liter as arsenic III was lethal to amphipods within 1 week. The same concentration of arsenic supplied as arsenic V, disodium methanearsonate (DSMA), or sodium dimethyl arsonate (SDMA) did not significantly decrease the survival of amphipods (*Gammarus pseudolimnaeus*) and *Daphnia magna* after 2 weeks of exposure, or other species including stoneflies, snails, and rainbow trout after 28 days.

## Fosamine Ammonium



$$CH_3\text{-}CH_2\text{-}O\text{-}\overset{\overset{O}{\uparrow}}{\underset{\underset{O\text{-}NH_4}{|}}{P}}\text{-}\overset{\overset{O}{\|}}{C}\text{-}NH_2$$

**Fosamine Ammonium**

Fosamine ammonium is a new herbicide that is expected to be increasingly used in forestry. It is registered for control of a wide variety of woody vegetation. It is usually applied as a foliar spray either by aerial or ground equipment during the 2 months before fall coloration. Rates of application of 3.36 to 6.72 kg/ha are common. National Forest Products Association (see footnote 3) and Newton (1981) discuss the use of fosamine ammonium in more detail.

### Behavior in the Environment

Fosamine ammonium is highly water soluble (179 g/100 g at 25 °C) with substantially less solubility in nonpolar organic solvents (0.02 g in 100 g n-hexane at 25 °C). It has little vapor pressure ($4 \times 10^{-6}$ mmHg at 25 °C).

Fosamine ammonium is not persistent in soils; laboratory studies indicate the mechanism of disappearance is rapid decomposition by soil microorganisms (Han 1979a). In greenhouses, a half-life of about 10 days has been recorded. In field studies in Delaware, Illinois, and Florida, a half-life of about 1 week was found for the parent compound (Han 1979a). Fosamine ammonium shows only limited mobility in column leaching studies. After 56 cm of leaching water had been applied, 60 to 80 percent of the herbicide was contained in the top 10-cm zone of the soil column. After 1 year and 165 cm of rain in the field, 93 percent of the chemical present was in the top 10 cm of soil. Studies of leaching in soil columns showed that fosamine ammonium is readily bound by soil particles and, despite its high water solubility, has little tendency to leach. The probability of ground-water contamination or movement of fosamine ammonium to streams by leaching is negligible.

Field data on stream contamination with fosamine ammonium are lacking, but because direct application and drift are probably the principal routes of entry, the data base for 2,4-D is probably applicable. Fosamine ammonium undergoes decomposition in water. In laboratory tests, fosamine ammonium (pH 5) was completely degraded in 2 weeks. At more neutral pH's, however, the compound was quite stable in water (Han 1979a). A strong interaction of fosamine ammonium with soil suggests it is likely to be adsorbed on suspended sediments or stream-bottom sediments where it enters forest streams. Stream-bottom sediments lose fosamine in 3 months or less.[11]

Specific information on bioaccumulation of fosamine ammonium is limited; as with other pesticides of high water solubility, however, the probability of bioaccumulation is limited. Laboratory tests have demonstrated that fosamine ammonium is not bioaccumulated. Residues in fish tissues were comparable to the concentration of the herbicide in water (Newton and Norgren 1977). Residues in channel catfish exposed to 1.1 mg/liter $^{14}C$-carbonyl-labeled fosamine ammonium in water for 4 weeks were found to plateau in 2 to 3 weeks, with an accumulation factor (ratio of residue in fish to residue in water) of less than 1. In a separate experiment, channel catfish were placed for 4 weeks in a tank containing ($^{14}C$) fosamine-ammonium-treated soil (15 mg/liter) that had been aged for 30 days before flooding and initiation of fish exposure. The residue levels in this group of catfish also reached a plateau in 2 to 3 weeks with an accumulation factor of less than 1. In both experiments, after the 4-week exposures, the fish were transferred to fresh water for 2-week depuration periods, during which residue levels dropped 50 to 90 percent. No effects on the fish were observed during these experiments (Han 1979b). In rats, fosamine ammonium was rapidly excreted (0.05-percent retention in body beyond 72 hours) (Chrzanowski et al. 1979).

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[11] Unpublished data of J. Harrod, Biochemicals Dep., 1007 Market St., Wilmington, Del., 1979.

## Toxicity

There is little published data on the toxicity of fosamine ammonium to fish. Unpublished findings of E. I. duPont de Nemours and Company, Inc.,[12/] indicate that rainbow trout and fathead minnows have a 96-hour $LC_{50}$ of 1000 mg/liter (product); bluegills exhibit a 96-hour $LC_{50}$ of 670 mg/liter (product).

In a recent series of laboratory bioassays, McLeay and Gordon (1980) added extensively to the toxicity data for Krenite with their partial life-cycle studies of coho salmon (egg through smolt) and rainbow trout (egg through fingerling). Highlights from their study are as follows:

- For both fish species, the alevin (yolk-sac fry) was the stage most sensitive to fosamine ammonium; 4-day median lethal concentrations ($LC_{50}$), including postexposure mortality, were 618 (coho) and 367 (rainbow) mg/liter.
- Egg stages were generally highly tolerant of fosamine ammonium.
- Swim-up fry and young fingerlings of both species were somewhat more tolerant to fosamine ammonium than was the alevin stage--yearling coho presmolts were slightly more tolerant than coho fingerlings (4-day $LC_{50}$ values of 7014 and 5361 mg/liter, respectively); coho smolts showed a minor increase in sensitivity compared to the presmolt stage.
- Postexposure mortalities occurred after a 4-day exposure of all life stages of each salmonid species to fosamine ammonium.
- No groups surviving previous exposure to fosamine ammonium showed any latent effects throughout the observation period in fresh water.
- Four-day $LC_{50}$ values for swim-up fry exposed to fosamine ammonium varied 12-fold when the diluent waters varied in pH, hardness, and alkalinity (increases in toxicity were related to increases in pH, alkalinity, and hardness).
- Comparison of the acute toxicity of fosamine ammonium with other brush-control herbicides (2,4-D, 2,4,5-T, silvex, picloram, amitrole, and glyphosate) to salmonid fish indicated that fosamine ammonium was 2 to 4 orders of magnitude less toxic.

In another study, no mortality was observed in yearling coho salmon exposed to concentrations up to 200 mg/liter of fosamine ammonium (Lorz et al. 1979) nor was subsequent survival in seawater affected.

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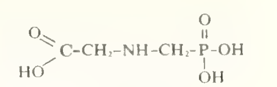
[12/] Unpublished data of E. I. DuPont de Nemours and Co., Inc., Biochemicals Dep., 1007 Market St., Wilmington, Del., 1979.

# Glyphosate



$$\mathrm{HO(O{=})C{-}CH_2{-}NH{-}CH_2{-}P({=}O)(OH){-}OH}$$

Glyphosate

Glyphosate is a new herbicide that is expected to be used increasingly in forestry. It is proving useful for both site preparation and release treatments at rates of application up to 4.48 kg/ha. National Forest Products Association (see footnote 3) and Newton (1981) discuss the use of glyphosate in more detail; Chykaliuk et al. (1981) have published an extensive bibliography on this chemical.

## Behavior in the Environment

Glyphosate is highly water soluble (12 000 mg/liter at 25 °C) with much lower solubility in organic solvents. It has negligible vapor pressure.

In general, glyphosate is very immobile in soil, rapidly adsorbed by soil particles, and subject to some degree of microbial degradation. Sprankle et al. (1975a, b) showed glyphosate was rapidly inactivated in soil, apparently by physical adsorption processes, because autoclaving the soil did not stop the inactivation. Addition of phosphate to the soil altered the availability of the glyphosate (Hance 1976). The initial binding of glyphosate to the soil was reversible, with phosphate ions competing for binding sites. Thus, the initial rapid inactivation of glyphosate in soil probably results from rapid adsorption rather than degradation. Some microbial degradation of the herbicide does occur in soil--45-percent degradation occurs in 28 days, according to Sprankle et al. (1975a, b). They also showed by thin-layer chromatography that glyphosate was immobile in soil.

Moshier and Penner (1978) reported decomposition of glyphosate was substantially different in different soils. After 32 days, the rate of decomposition in three soils was 40, 9.5, and 3 percent of the amount originally added. Rueppel et al. (1977), reporting on extensive work in both soil and water, found the degree of glyphosate decomposition in soils ranged from 5 to 50 percent in 28 days, depending on the soil. In two of three soils examined, 90 percent of the chemical was dissipated in less than 12 weeks. Aminomethylphosphonic acid was the only significant soil metabolite of glyphosate, and it degraded 16 to 35 percent in 60 days in various soils. The authors classified the chemical as immobile in soil, based on leaching experiments. These findings on the behavior of glyphosate in soil are consistent with the research reported by Torstensson and Aamesepp (1977) and Hance (1976).

Glyphosate was applied to an agricultural watershed at 1.10, 3.36, and 8.96 kg/ha (Edwards et al. 1980), and runoff from natural rainfall after treatments in early spring was measured and analyzed to define concentration and transport. The highest concentration (5.2 mg/liter) was found in runoff occurring 1 day after treatment at the highest rate. Glyphosate (0.004 mg/liter) was detected in runoff from this watershed up to 4 months after treatment. For the lower rates of application, maximum concentration of the herbicide in runoff was 0.094 mg/liter for events occurring 9 to 10 days after application, and decreased to 0.002 mg/liter within 2 months of treatment. The maximum amount transported by runoff was 1.85 percent of the amount applied, most of which occurred during a single storm on the day after application of the highest rate of glyphosate (8.96 kg/ha). In each of the three study years, herbicide transported in the first runoff event after treatment accounted for 99 percent of the total herbicide runoff on one watershed. Glyphosate residues in the upper 2.5 cm of treated soil decreased logarithmically with time; they persisted several weeks longer than in the runoff water.

Most of the data on the fate of glyphosate in water come from canal studies where glyphosate was used for weed control on banks. Comes et al. (1976) looked for both glyphosate and its principal metabolite in the first flow of water through two canals, after applications of 5.6 kg/ha to ditch banks when the canals were dry. Some of the herbicide was applied to surfaces of the canal that would be below the normal waterline. No glyphosate or metabolite was detected in the first flow of water through the canals. Soil samples collected the day before the canals were filled (about 23 weeks after treatment) contained 0.35 mg/liter glyphosate and 0.78 mg/liter metabolite in the 0- to 10-cm layer. When glyphosate was added to flowing canal water (sufficient to achieve 150 μg/liter), about 30 percent of the herbicide was lost in 1.6 km of travel. Thereafter, the rate of disappearance diminished; about 58 percent was present 8 and 14 km downstream from the introduction sites on two study canals, which implies interaction between the concentration and the mechanism of loss. Rueppel et al. (1977) reported less than 0.02 percent of applied glyphosate was removed in runoff processes from soil after artificial rain was applied at the rate of 1.9 cm/hour 1, 3, and 7 days after application of chemical.

Sacher (1978) summarized the behavior and impact of glyphosate in the aquatic environment. He reported glyphosate dissipated rapidly in static water, following first-order kinetics; the half-life of glyphosate in the pond was 12 days.

Relatively little has been done on the bioaccumulation of glyphosate, primarily because its physical-chemical properties are such that bioaccumulation is not expected to be substantial. Studies of fish metabolism demonstrated that glyphosate has an extremely low bioaccumulation factor. In three fish species--channel catfish, largemouth bass, and rainbow trout--the maximum levels of glyphosate, after 14 days exposure to 10 mg/liter, did not exceed 0.55, 0.12, and 0.11 mg/liter, respectively. These represent bioaccumulation factors of less than 0.18 (Sacher 1978).

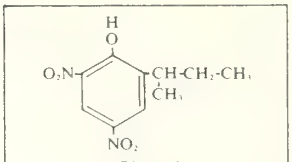
No residues of glyphosate or its primary metabolite (aminomethylphosphonic acid) were detected in the fillets or eggs of rainbow trout exposed to the isopropylamine salt (Folmar et al. 1979). In rainbow trout exposed to 2.0 mg/liter of Roundup, however, the fillets contained 80 mg/kg of glyphosate and the eggs contained 60 mg/kg, representing accumulation factors of 40 and 30. Midge larvae collected in drift and substrate samplers for 7 days after exposure to 2.0 mg/liter did not contain detectable glyphosate residues (Folmar et al. 1979).

### Toxicity

Folmar et al. (1979) conducted studies to determine the acute toxicity to four aquatic invertebrates and four species of fish of glyphosate, the isopropylamine salt of glyphosate, the formulated herbicide Roundup, and the Roundup surfactant. The 96-hour $LC_{50}$ values for Roundup varied from 2.3 mg/liter for the fathead minnow to 13 mg/liter for the channel catfish to 43 mg/liter for mature scuds (Gammarus pseudolimnaeus). Rainbow trout were intermediate in sensitivity. Technical-grade glyphosate, the active ingredient in Roundup, was less toxic than Roundup or the surfactant; the 96-hour $LC_{50}$ for rainbow trout was 140 mg/liter (glyphosate) and 2 mg/liter (surfactant). Roundup was more toxic to rainbow trout and bluegills at higher test temperatures, and was more toxic at pH 7.5 than at pH 6.5. Eyed eggs of rainbow trout were the most resistant life stage, and sensitivity increased as the fish entered the sac-fry and swim-up stages. In avoidance studies, rainbow trout did not avoid concentrations of the isopropylamine salt up to 10.0 mg/liter; mayfly nymphs avoided Roundup at concentrations of 10 mg/liter, but not at 1.0 mg/liter.

In a simulated aerial application of Roundup to a forested area, Hildebrand et al. (1980) found no detectable effects on Daphnia magna in a forest pond after application of 2.2, 22, and 220 kg/ha.

## Dinoseb



Dinoseb

Dinoseb is a contact-action herbicide available in two forms--free phenol and amine or ammonium salt of the phenol. Its only registered use in forestry is as a desiccant before burning for forest-site preparation (State of Oregon only). Although its scope of use is limited, it is included in this paper because of its high toxicity to aquatic species and its use in areas of important anadromous fish habitat.

### Behavior in the Environment

The phenol form of dinoseb has substantial vapor pressure (0.01 mmHg at 78 °C) and is soluble to 52 mg/liter in water, 23.4 percent in ethyl alcohol, and 8.7 percent in diesel fuel at 25 °C (Melnikov 1971). The salt forms are highly soluble in water and have substantially less vapor pressure. Interconversion between the salt and free phenol forms is expected, depending on the pH of the medium and the presence of other ions.

Dinoseb is subject to volatilization from soil. Hollingsworth and Ennis (1953) showed that this process depended on ambient temperature, moisture content of the soil, and the formulation applied. It was attributed to water-vapor distillation by Barrons et al. (1953) and did not occur at soil pH above 8.

The residual life of dinoseb is 3 to 5 weeks in warm, moist soils. Carryover from one season to the next is not expected (Klingman and Ashton 1975). Dinoseb is not tightly adsorbed on most agricultural soils, and it can leach in many sandy soils; Davis and Selman (1954) reported that the phenol form moved less than 2 cm with 5 cm of rain in any soil they tested. The amine salt, however, leached 3.8 cm in sandy loam, 6.3 cm in clay loam, and 8.9 cm in loam after the same amount of rain. Upchurch and Mason (1962) reported dinoseb interacted strongly with soil organic matter. Dinoseb was almost completely adsorbed at pH 2.3. In zones of moderate temperature and rainfall, and at normal rates of application, dinoseb should not be leached from the top foot of the acid forest soils of the Pacific Northwest in the 1st year after application. Substantial decomposition by microbial action takes place within the 1st year of application. Phytotoxic levels may remain in soil from 2 weeks to 6 months, depending on the environment in which it is used.

We found no published information on the levels or persistence of dinoseb in stream water. We assume 2,4-D is a reasonable model for dinoseb because direct application and drift are probably the main routes of entry into streams.

Data on dinoseb bioaccumulation are lacking. In the phenol form, bioaccumulation during periods of exposure should be expected. In the salt form, this behavior will be less pronounced. Lorz et al. (1979) found measurable residues of dinoseb in a few coho salmon exposed to 0.02 mg/liter of dinoseb for 384 hours. Most samples did not contain detectable residues (levels ranged from less than 0.01 to 0.03 mg/kg in gill, 0.37 mg/kg in kidney, 0.4 mg/kg in liver, and 1.4 mg/kg in spleen).

## Toxicity

Dinoseb is more toxic to humans, animals, and fish than most herbicides. The acute and chronic effects of dinoseb on cutthroat and lake trout were investigated by Woodward (1976), who found that toxicity of a given exposure was greatly influenced by water quality. Decreasing the pH of the water resulted in a corresponding increase in dinoseb toxicity to fish. Similar findings were reported by Lipschuetz and Cooper (1961) for technical-grade dinoseb. Decreasing the pH from 8.0 to 6.9 increased the toxicity of dinoseb to rainbow trout by a factor of 5. High temperature and hardness of the water also tend to maximize the toxicity of dinoseb to fish, but to a lesser extent than pH (Webb as cited by Lipschuetz and Cooper 1961, Woodward 1976).

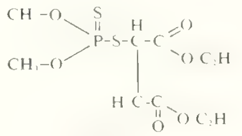
The 96-hour $LC_{50}$'s, under varying conditions of pH, temperature, and hardness, ranged from 0.41 to 1.35 mg/liter dinoseb for cutthroat trout and from 0.032 to 1.40 mg/liter for lake trout (Woodward 1976). Lipschuetz and Cooper (1961) observed similar dinoseb values for rainbow trout. Their 24-hour $LC_{50}$ at pH 8.0 was 0.30 mg/liter (technical) and at pH 6.9 was 0.073 mg/liter (18 °C). Western blacknose dace in water of pH 8.0 and 21 °C had a 24-hour $LC_{50}$ of 0.24 mg/liter dinoseb (technical). Using a dinoseb formulation composed of secondary butyl dinitrophenol and secondary amylbutyl dinitrophenol, Lipschuetz and Cooper (1961, citing the 1955 work of Webb) reported a 24-hour $LC_{50}$ for redside shiners of 0.16 mg/liter in soft water (18 mg/liter hardness, pH 7.6) and of 0.24 mg/liter in hard water (105 mg/liter hardness, pH 8.2).

Woodward (1976) observed no cumulative mortality of lake and cutthroat trout with chronic exposures (8 to 12 days) to dinoseb. Prolonged exposures of 0.005 to 0.010 mg/liter dinoseb, however, affected yolk absorption time and fry growth. Yolk absorption time increased by 6 to 9 days over that of the controls, and fry growth was reduced at all concentrations of dinoseb tested.

Lorz et al. (1979) calculated the 24-hour $LC_{50}$ of dinoseb to yearling coho salmon to be 0.190 mg/liter, and the 144-hour $LC_{50}$ was estimated to be 0.088 mg/liter (under static conditions) at 10 °C and pH 7.0. When survivors of this bioassay were challenged with seawater, no mortalities occurred. In a flowing-water system, the toxicity of dinoseb appeared greater--93 percent of coho salmon yearlings exposed for 6 days to 0.060 mg/liter died, and all were dead in 16 days; in the group exposed to 0.040 mg/liter, 94 percent died during the 16-day exposure. Releasing dinoseb-exposed coho salmon and monitoring their downstream movement showed that groups exposed to 0.040 and 0.060 mg/liter for 48 hours were less migratory than the controls. Yearling coho salmon exposed to 0.100 mg/liter for 114 hours showed extensive necrosis of the liver, kidney, and gill lamellae; however, examination of tissues of fish exposed to 0.040 and 0.060 mg/liter showed only minor degenerative changes.

## INSECTICIDES

### Malathion



Malathion

Malathion is an organophosphate insecticide that receives extensive use in both agriculture and forestry. It has been available for use since 1959. Information on the use and impact of malathion in the forest are in two environmental impact statements (U.S. Department of Agriculture, Forest Service 1976; U.S. Department of Agriculture, Animal and Plant Health Inspection Service, 1980). The most recent uses of malathion on lands managed by the Forest Service have been for control of western spruce budworm and grasshoppers on western forests and ranges (aerially applied at 0.8 kg/ha).

### Behavior in the Environment

Various aspects of the behavior of malathion in the environment are cited in several chapters of Haque and Freed (1975). Malathion has a vapor pressure of $4 \times 10^{-5}$ mmHg (30 °C) and a water solubility of 145 mg/liter. It is soluble in most organic solvents, but is of limited solubility in petroleum oils.

Malathion disappears rapidly from soil, probably by both chemical and biological means. Konrad et al. (1969) reported 50- to 90-percent disappearance in 24 hours, in both sterile and nonsterile soil systems, depending on the type of soil. Malathion disappears rapidly from soil even at high rates of application. Roberts (1962) reported malathion applied to the soil from a tractor-mounted sprayer at 85.8 kg/ha completely disappeared after 6 months; only 3.1 kg/ha remained after 1 month. Both the persistence and mobility of malathion were determined at land waste-water disposal sites where the chemical was applied by sprinkler irrigation for long periods. In these tests, the chemicals were applied (0.1 mg/liter) in the secondary effluent from a two-stage trickling filter for 15 weeks. Malathion was never present in excess of 0.002 mg/kg in the soil and 0.001 mg/liter in the soil water. These results indicate malathion will neither accumulate in soil nor translocate in soil waters under the types of conditions tested (Jenkins et al. 1978).

Concentrations of malathion in stream water were monitored in connection with the spruce budworm control projects conducted in the State of Washington in 1976 (table 8). Tracy et al. (1977) reported the peak concentrations of malathion in streams without buffer strips were 0.037 to 0.042 mg/liter; in streams with buffer strips, peak concentrations ranged from nondetectable to 0.017 mg/liter. Residues were not detected in most of the 48-hour postspray samples. No residues were found in fish or benthic organisms from these streams.

Table 8--Peak concentrations of malathion and Sevin-4-Oil in stream water as affected by stream size and buffering, Okanogan and Wenatchee National Forests[1]

| Chemical and stream | Streamflow | Protection | Peak concentration |
|---|---|---|---|
| | Cubic meters per second | | Micrograms per liter |
| Malathion:[2] | | | |
| Hansel Creek | 0.34 | Nonbuffered | 37 |
| Gold Creek | .11 | Nonbuffered | 42 |
| Nason Creek | 25 | Buffered | 3 |
| Little Bridge Creek | .57 | Buffered | 0 |
| Taneum Creek-- | | | |
| Spray day 1 | 3.3 | Buffered | 17 |
| Spray day 3 | 3.3 | Buffered | 4 |
| Teanaway River-- | | | |
| Spray day 1 | 5.1 | Buffered | 1 |
| Spray day 2 | 5.1 | Buffered | 21 |
| Sevin-4-Oil:[3] | | | |
| Gate Creek | .14 | Nonbuffered | 11 |
| Yellow Jacket Creek | .01 | Nonbuffered | 5 |

[1] Tracy et al. (1977).
[2] Malathion applied as ultralow-volume spray, 13 oz/acre (0.91 kg/ha).
[3] Sevin-4-Oil (carbaryl) applied at about 1 lb/acre (1.12 kg/ha).

Eichelberger and Lichtenberg (1971) determined the persistence of malathion in river water. When the malathion was added at 0.010 mg/liter, 0.002 mg/liter was observed after 1 week, 0.001 mg/liter was measured after 2 weeks, and no detectable residue was found after 4 weeks. In a soil-free, aqueous system that had been inoculated with a soil extract, malathion disappeared in two phases; a relatively slow phase accounted for about 30 percent disappearance in 180 hours, and a more rapid phase accounted for more than 50 percent disappearance in the next 60 hours. Degradation in the aquatic system would have represented both chemical degradation (the slow phase) and microbial degradation (the rapid phase). Freed et al. (1979) reported half lives of malathion of 1.3 days at 37 °C and 11 days at 20 °C, when the pH was 7.4 (in a laboratory system that would be expected to have low biological activity). At pH 6.1, the half-life of malathion was 120 days. Konrad et al. (1969) reported a similar effect of pH on malathion persistence in aqueous systems. In a more natural aqueous system, however, they reported more than 90-percent decomposition of malathion in the water in 230 hours. Walker (1978) reported malathion was the shortest lived of the insecticides tested in both fresh and salt water. Half lives in his system varied from 11 days in fresh water to less than 2 days in saline water.

Malathion is expected to show little bioaccumulation. Kenaga (1980a, b) predicted a bioconcentration factor of 37. Paris et al. (1975) found no measurable absorption of malathion by dense populations of microorganisms. The high water solubility and the low fat solubility of malathion will result in its rapid excretion or elimination from organisms that have accumulated it. Residues of malathion have been found in milk collected from cattle 5 hours after they were sprayed at rates several times the normal rate used in aerial applications in forestry. Only trace amounts were found 3 days after treatment. The rapid disappearance of the insecticide was attributed to its rapid excretion by the animal. The short persistence of malathion in the aquatic environment will also be an important factor in limiting its bioaccumulation.

## Toxicity

Hoffman (1957), Stavinoha et al. (1966), and Livingston (1977) reviewed the literature and noted that the organophosphate insecticides were generally short lived in the environment, did not significantly bioaccumulate or biomagnify, and had a relatively uniform and well-understood effect on a variety of organisms. The "safe" concentrations of organophosphate insecticides have been estimated through acute toxicity studies and determination of environmental persistence (Benson 1969). Although the acute toxicity of these compounds to aquatic organisms is generally lower than the organochlorines, it varies widely (Tarzwell 1958, Pickering et al. 1962, Macek and McAllister 1970, Johnson and Finley 1980).

Toxic action to various species has been associated with specific reactions to synergistic or antagonistic effects between the parent compounds and hydrolysis products. Numerous studies have shown that cholinesterase is the primary site of action of the organophosphate compounds. Symptoms of acute toxicity vary from species to species, however, and diverse formulations have different acute effects.

Eaton (1970) conducted a study of chronic malathion toxicity to bluegills similar to the study by Mount and Stephan (1967) on the fathead minnow. In Eaton's study, concentrations of 66 and 28 μg/liter were lethal to all fish within 16 and 54 days, respectively, and some were killed at 15 μg/liter. Reproduction and early fry survival were unaffected by the 7.4 μg/liter concentration that crippled adult fish after exposure for several months.

Mulla and Mian (1981) synthesized and interpreted much of the available information on the impact of malathion and parathion on nontarget flora and fauna in aquatic ecosystems, as well as the persistence and distribution of these chemicals in aquatic habitats. Malathion was shown to have low toxicity to several mollusks, but was considerably more toxic to crustaceans (water fleas, amphipods, shrimp, and juvenile crabs). Immature nontarget insects, such as caddisflies, stoneflies, and mayflies, were highly sensitive. Malathion exhibited differential toxicity to various fish species; some species showed a substantial degree of tolerance.

Although malathion is a widely used organophosphate insecticide entering surface waters in various ways, residue interpretation is difficult because of the toxicity of a "persistent" metabolite (malaoxon), which is not easily identified in tissues. Cook et al. (1976) suggested alternate methods of analysis, including analysis for malathion monoacid in the gut and measurement of brain acetylcholinesterase activity, because the parent compound is rapidly absorbed and altered by fish. Bender (1969) found that a basic hydrolysis byproduct of malathion, with a pronounced synergistic effect demonstrated between malathion and its two hydrolysis products, was more toxic to fathead minnows than the parent compound. Bender and Westman (1976) found that malathion could damage eastern mudminnows through either acute or chronic toxicity at concentrations of 0.09 to 0.24 mg/liter (the $LC_{50}$'s of malathion and its principal hydrolysis products). Desi et al. (1976) found that although malathion was only slightly toxic to guppies, it was highly toxic to invertebrates such as Daphnia magna ($LC_{50}$ 0.003 mg/liter) and to juvenile forms of various species. They found that malathion affects aquatic organisms differently and, by exerting stress on "sophisticated functions" and exhausting the adaptability of such organisms, it is "not an entirely harmless agent for the environment." Table 9 summarizes some of the data on acute toxicity available for malathion to important invertebrate and fish species.

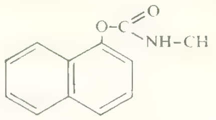
Table 9--Acute toxicity of malathion to various invertebrate and fish species

| Test organism | Stage or weight | Temperature | 96-h $LC_{50}$ | Reference |
|---|---|---|---|---|
| | Grams | Degree C | mg/liter | |
| Invertebrates: | | | | |
| *Daphnia magna* | I[1] | 15 | [2]0.0010 | Johnson and Finley 1980 |
| *D. pulex* | I[1] | 15 | [2].0018 | Johnson and Finley 1980 |
| *Asellus* sp. | M[3] | 21 | 3.0 | Johnson and Finley 1980 |
| *Gammarus fasciatus* | M[3] | 21 | .00076 | Johnson and Finley 1980 |
| *Isoperla* sp. | YC[4] | 15 | .00069 | Johnson and Finley 1980 |
| *Limnephilus* sp. | J[5] | 15 | .0013 | Johnson and Finley 1980 |
| Fish: | | | | |
| Chinook salmon | 1.4-5 | 20 | .023 | Katz 1961 |
| Coho salmon | .9 | 12 | .17 | Johnson and Finley 1980 |
| Coho salmon | .6-1.7 | 13 | .101 | Macek and McAllister 1970 |
| Cutthroat trout | 1.0 | 12 | .28 | Johnson and Finley 1980 |
| Rainbow trout | 1.4 | 12 | .20 | Johnson and Finley 1980 |
| Rainbow trout | .6-1.7 | 13 | .20 | Macek and McAllister 1970 |
| Lake trout | .3 | 12 | .076 | Johnson and Finley 1980 |
| Brown trout | 1.1 | 12 | .101 | Johnson and Finley 1980 |
| Brown trout | .6-1.7 | 13 | .20 | Macek and McAllister 1970 |
| Fathead minnow | .9 | 18 | 8.650 | Johnson and Finley 1980 |
| Fathead minnow | 1-1.5 | 25 | 12.5 | Henderson and Pickering 1958 |
| Fathead minnow | 1-2 | 25 | 23 | Pickering et al. 1962 |
| Black bullhead | 1.2 | 18 | 12.9 | Johnson and Finley 1980 |
| Bluegill | 1-2 | 25 | .09 | Pickering et al. 1962 |
| Bluegill | 1.5 | 18 | .103 | Johnson and Finley 1980 |
| Bluegill | 1.5 | 25 | .095 | Henderson et al. 1959 |
| Walleye | 1.3 | 18 | .064 | Johnson and Finley 1980 |
| Yellow perch | 1.4 | 18 | .263 | Johnson and Finley 1980 |

[1] First instar.
[2] 48-hour $EC_{50}$.
[3] Mature.
[4] First-year class.
[5] Juvenile.

Johnson and Finley (1980) noted that 0.3-g lake trout fry were twice as sensitive to malathion as 45-g fingerlings. An increase in temperature from 7 °C to 29 °C caused a 4-fold increase in toxicity to bluegills. Variations in water hardness did not appreciably alter the toxicity to fish or invertebrates. Salmonids exposed to 0.120 to 0.300 mg/liter malathion showed 70- to 80-percent inhibition of acetylcholinesterase (AChE), and activity indexes were reduced by 50 to 70 percent of that of unexposed fish. Goldfish exposed to sublethal levels showed a significantly reduced avoidance response at levels below that causing a reduced AChE activity. Exposures of rainbow trout to sublethal levels of malathion for 1 hour caused severe tissue damage to the gills and minor nonspecific liver lesions. Ponds given four semimonthly treatments up to 0.02 mg/liter during May through July produced no discernible effects on resident bluegills or channel catfish. Populations of aquatic insects, however, were significantly depressed by high but not low treatment rates. These data indicate that use of malathion needs careful planning because some species and habitat-specific reactions to this pesticide can cause adverse effects.

# Carbaryl



Carbaryl

Carbaryl is a broad-spectrum, relatively nonpersistent carbamate insecticide that has been used for nearly 30 years to suppress various types of insect infestations. Registered for use against many insects, its principal use in agriculture is at rates of 0.5 to 2.24 kg/ha active ingredient, often in repeated spray treatments. In forestry, it is used to control defoliating insects (U.S. Department of Agriculture, Forest Service 1976). Forest-application rates of more than 1.12 kg/ha are uncommon. In fiscal year 1980, most of the carbaryl used in Forest Service programs was aerially applied for grasshopper control on western forest and range lands. Mount and Oehme (1981) published an extensive literature review on carbaryl--its chemistry, toxicity, metabolism, environmental degradation, and so on.

## Behavior in the Environment

Carbaryl is soluble in most polar organic solvents and to about 0.01 percent in water. In the soil, carbaryl is attacked by soil microbes and is not expected to leach significantly from the upper soil surfaces. Bollag and Liu (1971) isolated several microorganisms capable of metabolizing carbaryl in soil. A half-life of about 12 days was noted in several of these systems. In soil, carbaryl has shown a half-life of about 8 days for application rates ranging from 3.36 to 30.2 kg/ha (Union Carbide 1968). Carbaryl was detected in soil and the forest floor for 64 and 128 days, respectively, after application (Willcox 1972). Goring et al. (1975) estimated the persistence of several pesticides in soil, based on a search of many references. They indicate the estimated time required for 50-percent disappearance of carbaryl from soil ranged from 1.5 to 6 months.

LaFleur (1976) studied carbaryl movement and loss in the soil profile and its accumulation in underground water over a 16-month period. Rainfall during the study was 182 cm. The upper 1 m of soil contained about 6 percent of the applied carbaryl 16 months after application. None was found in the 10- to 20-cm layer after the 4th month. Loss of carbaryl with time in the upper 1 m of soil depended on concentration, and the half-life was less than 1 month. In underlying ground water, carbaryl appeared within 2 months after application and persisted through the 8th month. The maximum ground-water concentration was 0.3 μmole/liter at the end of the 2d month.

No carbaryl was detected in the field plot or soil water at a land wastewater disposal site that received carbaryl (0.1 mg/liter in water) over a 15-week period (Jenkins et al. 1978). The authors concluded that carbaryl does not accumulate or translocate under the field conditions of this test. Haque and Freed (1974) predicted carbaryl will leach less than 20 cm in the soil profile that receives an annual rainfall over 150 cm.

Caro et al. (1974) reported 95 percent of the carbaryl in an agricultural soil had disappeared within 135 days. Of the 4 kg of carbaryl applied, 5.8 g were recovered during the 1st year in runoff water and sediment. Over 90 percent of this loss occurred in a single rainfall 19 days after application. About 75 percent of the seasonal loss was contained in water and 25 percent in sediment.

Paris et al. (1975) indicated carbaryl was degraded both chemically and biologically; the rate of biological degradation was proportional to the density of microorganisms. Chemical degradation predominated in their study. The persistence of carbaryl in water appears to be brief. If carbaryl is applied over open water, such as small brooks or ponds, initial deposits of 1 mg/liter or less in water depths of about 10 cm may be expected to degrade completely or disappear in 1 or 2 days (Lichtenstein et al. 1966).[13, 14] Eichelberger and Lichtenberg (1971), in determining the persistence of several insecticides in river water, found only 5 percent of the original 0.01 mg/liter of carbaryl remained 1 week after application. No residues were detected after 2 weeks. Romine and Bussian (see footnote 13) found no detectable carbaryl in the water of a farm pond 2 days after it had been sprayed at the rate of 6.7 kg/ha. Residues immediately after spraying were 4.8 mg/liter. Residues in the sediment disappeared after 4 days.

Karinen et al. (1967) reported the concentration of carbaryl in estuarine water decreased 50 percent in 38 days. When mud was present, more than 90-percent loss occurred in 10 days. The carbaryl was adsorbed where decomposition continued at a slower rate. The principal metabolite of carbaryl, 1-napthal, was less persistent. Carbaryl applied (11.2 kg/ha) to a tidal mud flat disappeared rapidly. The initial residue level of 10.7 mg/kg decreased rapidly the 1st day when the tide removed carbaryl, and the 1-napthal metabolite was not adsorbed on mud. The level in the top 2.5 cm of mud decreased from 3.8 mg/kg 1 day after treatment to 0.1 mg/kg by the 42d day.

Carbaryl was monitored in stream and pond water in the Eastern United States. Values ranged from nondetectable to 0.03 mg/liter; most values were around 0.001 mg/liter (Tracy et al. 1977). In the Pacific Northwest, Tracy et al. (1977) reported 0.005 to 0.011 mg/liter as peak concentrations of carbaryl in streams in areas sprayed for control of western spruce budworm (table 8). These values were for streams without buffer strips. Residues were at or near detection limits in samples collected 48 hours after application. Tracy et al. (1977) did not find measurable carbaryl in aquatic insects from streams flowing through treated forest areas.

Where carbaryl was applied at 0.84 kg/ha for control of spruce budworm, Hulbert (1978) measured peak concentrations of 0.026 and 0.042 mg/liter in water, and Stanley and Trial (1980) detected peak concentrations of 0.0009 to 0.008 mg/liter in brooks (3 to 8 m wide) and 0.0004 to 0.002 mg/liter in rivers (15 to 100 m wide), shortly after application. Buffer strips of 150 m were used. Along one stream where no buffer strip was used, a peak concentration of 0.016 mg/liter was detected. The concentrations decreased exponentially with time after application. The half-life for carbaryl in these stream systems was

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[13] Unpublished report, "The degradation of carbaryl after surface application to a farm pond," Proj. Rep. 111A13, by R. R. Romine and R. A. Bussian, Union Carbide Corp., Salinas, Calif., 1971.

[14] Unpublished report, "An investigation into the effect on fish of Sevin (carbaryl) used in rice culture," Pittman-Robertson Proj. W-52-R, prepared by Resour. Agency, Wildl. Invest. Lab., Calif. Dep. Fish and Game, Sacramento, 1963.

23 hours in brooks and 28 hours in rivers. The rate constant ($0.028\ \text{hour}^{-1}$) reported by Stanley and Trial (1980) for carbaryl disappearance in streams was similiar to the decay constants determined in the laboratory for carbaryl in river water ($0.017\ \text{hour}^{-1}$) and pond water ($0.028\ \text{hour}^{-1}$) (Eichelberger and Lichtenberg 1971, Kanazawa 1975). Marancik[15] noted that Atlantic salmon, brook trout, and slimy sculpins did not contain detectable residues of carbaryl 24, 48, or 168 hours after aerial application of 1.12 kg/ha to forests in the Eastern United States.

Bernhardt et al. (1978) conducted a much more intensive study of carbaryl in six streams in Washington State. Peak concentrations of 0.005, 0.013, 0.014, 0.020, 0.029, and 0.121 mg/liter were observed within the treated area in these six streams. Residues typically declined from peak levels within a few hours after application. Residue levels were much lower at downstream locations. In Squilchuck Creek, the stream that received the greatest exposure, residues of 100 to 120 mg/kg were measured in benthic organisms, 131 to 152 mg/kg in cutthroat trout, and 32 to 335 mg/kg in sediment. Residues were not found in these substrates at most other locations and, with the exception of the sediment, were not found 30 days after application in Squilchuck Creek.

Kenaga (1980b) predicted a bioaccumulation factor of 77 for carbaryl. In a model aquatic ecosystem, Kanazawa et al. (1975) reported higher values. They found bioaccumulation ratios of 2,000:1 to 4,000:1 for algae and duckweed, but values of only 100:1 to 500:1 for snails, catfish, and crayfish. The sediment in the system was the major repository for the chemical. The data suggest that carbaryl was tightly bound to soil particles and humic substances. Daphnia, which are extremely sensitive to carbaryl, were unaffected when placed in clean water that had been in contact with the sediments from this test for 3 days.

In a similar system, Sanborn (1974) did not detect any unmetabolized carbaryl in several components (including algae) of the ecosystem, although several metabolic products were prominent. Paris et al. (1975) found no measurable adsorption of carbaryl by microorganisms. Exposures of channel catfish for 28 days to $^{14}$C-carbaryl in the diet (2.8 mg/kg) or by bath (0.25 mg/liter) produced whole-body residues of 9 and 11 µg/kg, respectively. Within 28 days, 78 percent of these residues were eliminated by the diet-exposed fish but only 11 percent by the bath-exposed fish (Johnson and Finley 1980). Korn (1973) found that channel catfish did not accumulate carbaryl because they metabolize or excrete the compound. Marancik, citing Tompkins (1975, see footnote 15), reported that pumpkinseed (sunfish) exposed to 5 mg/liter Sevin for 2 hours accumulated 12.6 mg/kg in the tissue by the end of the exposure period, but eliminated 99.8 percent within 24 hours after exposure ended. These data suggest carbaryl bioaccumulation will be limited and its persistence brief.

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[15] Unpublished report, "Effect of insecticides used for spruce budworm control in 1975 on fish," p. 11-34 in "1975 Cooperative Pilot Control Project of Dylox, Matacil, and Sumithion: forest spruce budworm control in Maine," by J. Marancik, U.S. Dep. Agric., For. Serv., Northeast. Area, Upper Darby, Penn., 1976.

Table 10--Acute toxicity of carbaryl to various invertebrate and fish species

| Test organism | Stage or weight | Temperature | 96-h $LC_{50}$ | Reference |
|---|---|---|---|---|
| | Grams | Degree C | mg/liter | |
| Invertebrates: | | | | |
| *Daphnia pulex* | I[1] | 16 | 0.0064 | Johnson and Finley 1980 |
| *Asellus* sp. | M[2] | 18 | .28 | Johnson and Finley 1980 |
| *Gammarus fasciatus* | M[2] | 21 | .026 | Johnson and Finley 1980 |
| *Pteronarcys* sp. | $YC_2$[3] | 16 | .0048 | Sanders and Cope 1968 |
| Fish: | | | | |
| Coho salmon | 1.0 | 13 | 4.34 | Johnson and Finley 1980 |
| Coho salmon | .6-1.7 | 13 | .764 | Macek and McAllister 1970 |
| Coho salmon | 2.7-4.1 | 20 | .997 | Katz 1961 |
| Cutthroat trout | .5 | 12 | 7.1 | Johnson and Finley 1980 |
| Cutthroat trout | -- | 9.5 | 6.7 | Woodward and Mauck 1980 |
| Rainbow trout | 1.5 | 12 | 1.95 | Macek and McAllister 1970 |
| Rainbow trout | 3.2 | 20 | 1.35 | Katz 1961 |
| Fathead minnow | .6-1.7 | 18 | 14.6 | Macek and McAllister 1970 |
| Fathead minnow | -- | -- | 6.7 | Henderson et al. 1960 |
| Fathead minnow | .8 | 18 | 14.6 | Johnson and Finley 1980 |
| Yellow perch | .6 | 12 | 5.1 | Johnson and Finley 1980 |
| Bluegill | 1.2 | 18 | 6.76 | Johnson and Finley 1980 |
| Bluegill | .7 | 17 | [4]39 | Johnson and Finley 1980 |
| Bluegill | .6-1.7 | 18 | 6.76 | Macek and McAllister 1970 |
| Bluegill | -- | -- | 5.3 | Henderson et al. 1960 |

-- = data not available.

[1] First instar.
[2] Mature.
[3] Second-year class.
[4] Contained in oil dispersion, 49 percent active ingredient.

## Toxicity

Table 10 summarizes the toxicity of carbaryl for several invertebrate and fish species.

Courtemanch and Gibbs (1980) noted short- and long-term effects on stream invertebrates after spraying with carbaryl. The initial postspray response was an increase in drift, and the benthos showed significant declines among Plecoptera, Ephemeroptera, and Trichoptera. Plecoptera did not repopulate any treated stream by 60 days posttreatment. These findings are similar to those of Burdick et al. (1960), who reported a reduction in standing crop of total stream invertebrates after forest spraying with Sevin. The long-term effect of the chemical was most apparent on Plecoptera, especially in streams treated for two consecutive years.

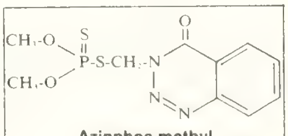
Stewart et al. (1967) studied the acute effects of carbaryl and its hydrolytic product 1-naphthal on various marine species. They found that carbaryl was more toxic to larval and adult crustaceans than to larval and adult mollusks and juvenile fishes. Carbaryl was more toxic than 1-naphthal. Carlson (1972) found that long-term exposure of fathead minnows to carbaryl at a concentration of 0.68 mg/liter caused adverse effects on survival and spawning.

The teratogenic effects of carbaryl and malathion on developing medaka embryos exposed in static tests were investigated by Solomon (1978) and Solomon and Weis (1979). The primary site of action of these insecticides was the circulatory system. Significant effects on circulatory anomalies were produced at concentrations of 5 mg/liter carbaryl and 20 mg/liter malathion.

Woodward and Mauck (1980) found stonefly naiads and amphipods were considerably more sensitive than cutthroat trout to carbaryl and thus would show the greatest impact after forest spraying that caused stream contamination. Johnson and Finley (1980) provided the following notes on carbaryl tests conducted at the Columbia Fisheries Research Laboratory:

> Little or no alteration in toxicity resulted when temperatures were increased from 10 to 21C for daphnids or from 7 to 17C for cutthroat trout and Atlantic salmon. Conversely, toxicity to brook trout and yellow perch was significantly increased (4- to 11-fold) by similar temperature increases. Increases in the pH of test solutions from 6.5 to 8.5 decreased toxicity to stoneflies by one-half. However, alkaline test solutions (pH 8.5 to 9.0) were 1.4 to 11.4 times more toxic to trout, salmon, and yellow perch than were test solutions with lower pH (6.5 to 7.5). Variations in hardness (12 to 300 mg/l) did not appreciably alter toxicity to scuds, trout, or yellow perch. Test solutions aged for 3 weeks were less toxic to stonefly naiads, yet more toxic to cutthroat trout.

## Azinphos-methyl



Azinphos-methyl

Azinphos-methyl is an organophosphate insecticide registered for use on a wide variety of plants to control many insect pests. It has been available since it was first registered for use on cotton in 1954; its most extensive use in forestry is in ground applications for control of seed and cone insects in seed production areas.

### Behavior in the Environment

A comprehensive review of the use and behavior of azinphos-methyl in American agriculture was made by Anderson et al. (1974). Inferences can be made to forestry uses. Azinphos-methyl is soluble to 29 mg/liter in water (25 °C) and is readily soluble in most organic solvents (except aliphatics).

The Chemagro Division of BayChem Corporation has conducted soil persistence studies of azinphos-methyl (Anderson et al. 1974). They report the average half-life of the compound was about 3 months, although it varied substantially in different soil types and in different geographic locations. In muck-sand soils of Florida, the reduction averaged more than 50 percent in 1 month. In clay soils of Louisiana, a 50-percent reduction required 3 months, but in Kansas clay soils, the time was between 2 and 3 months. Rainfall on the Louisiana plots was 24.4 cm; on the Kansas plots, it was 36.6 cm (Anderson et al. 1974). Haque and Freed (1974) estimate azinphos-methyl would leach less than 20 cm in soils receiving 150 cm of rainfall. Results of these tests suggest the persistence of azinphos-methyl and its mobility are not sufficent to result in either buildup of the compound in the soil or its transfer into ground water.

We did not find any published reports of azinphos-methyl in forest waters. There are unconfirmed reports of azinphos-methyl in surface and subsurface water draining from seed orchards on sandy soils in the southeastern United States. Its predominant pattern of use minimizes the likelihood that forestry uses of this insecticide will result in its residues entering forest surface waters in the West.

Meyer (1965) reported the half-life of azinphos-methyl would be about 2 days in the aquatic environment. In Meyer's study, the pH of the various ponds ranged from 7.2 to 8.0 and, Table 11--Acute toxicity of azinphos-methyl to various invertebrate and fish species

| Test organism | Stage or weight | Temperature | 96-h $LC_{50}$ | Reference |
|---|---|---|---|---|
|  | Grams | Degree C | mg/liter |  |
| Invertebrates: |  |  |  |  |
| *Asellus* sp. | M[1] | 15 | 0.021 | Johnson and Finley 1980 |
| *Gammarus fasciatus* | M[1] | 21 | .00015 | Johnson and Finley 1980 |
| *Pteronarcys* sp. | YC2[2] | 15 | .0019 | Johnson and Finley 1980 |
| Fish: |  |  |  |  |
| Coho salmon | 0.7 | 12 | .0061 | Johnson and Finley 1980 |
| Coho salmon | -- | 20 | .0042 | Katz 1961 |
| Coho salmon | .6-1.7 | 13 | .017 | Macek and McAllister 1970 |
| Rainbow trout | -- | 20 | .0032 | Katz 1961 |
| Rainbow trout | .6-1.7 | 13 | .0014 | Macek and McAllister 1970 |
| Rainbow trout | 1.0 | 12 | .0043 | Johnson and Finley 1980 |
| Fatnead minnow | 1-2 | 25 | .0093 | Henderson et al. 1960 |
| Fathead minnow | .6-1.7 | 18 | .235 | Macek and McAllister 1970 |
| Fathead minnow | 1.2 | 18 | .235 | Johnson and Finley 1980 |
| Bluegill | 1.5 | 18 | .022 | Johnson and Finley 1980 |
| Bluegill | .6-1.7 | 18 | .022 | Macek and McAllister 1970 |
| Bluegill | 1-2 | 25 | .0052 | Henderson et al. 1960 |
| Largemouth bass | .6-1.7 | 18 | .005 | Macek and McAllister 1970 |
| Largemouth bass | .9 | 18 | .0048 | Johnson and Finley 1980 |

-- = data not available.

[1] Mature.
[2] Second-year class.

after application of 1 mg/liter azinphos-methyl, the residues dropped from 0.8 mg/liter at 4 hours to 0.4 mg/liter at 48 hours after application. At 4 days, the residue level was 0.1 mg/liter and was nondetectable at 14 days. Flint et al.[16] reported a half-life of 1.2 days in an outdoor pond. The degradation was more rapid where both sunlight and microorganisms were active than in indoor tests. Liang and Lichtenstein (1972) showed azinphos-methyl was subject to photodecomposition in aquatic systems. These tests suggest that the decomposition of azinphos-methyl in an aquatic environment is relatively rapid, and accumulation is not expected. Iwata et al. (1977) reported that disappearance of azinphos-methyl followed first-order kinetics in a silty clay loam soil with a 100-fold decrease in concentration in 105 days.

Azinphos-methyl should show little potential for bioaccumulation. In dairy cattle, it appears to be rapidly excreted (Everett et al. 1966, Loeffler et al. 1966). No residues are found in milk 1 to 2 days after treated feed was withdrawn. This information, combined with what is known of the physical properties of azinphos-methyl, suggests that its bioaccumulation is not likely to be extensive, and it should clear rapidly from organisms once exposure ceases.

## Toxicity

Several researchers have studied the toxicity of azinphos-methyl to invertebrates and fishes (Henderson et al. 1960, Katz 1961, Macek and McAllister 1970, Johnson and Finley 1980). It is 2 to 10 times more toxic than malathion. Table 11 provides a summary of its acute toxicity to a variety of invertebrates and fishes.

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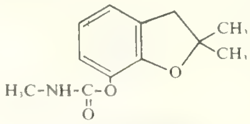
[16] Unpublished report, "Soil runoff, leaching, and adsorption and water stability studies with Guthion," Rep. 28936, by D. R. Flint, D. D. Church, H. R. Shaw, and J. Armour, Chemagro Corp., Kansas City, Mo., 1970.

Johnson and Finley (1980) noted that variations in test temperatures from 2 °C to 18 °C for rainbow trout and 12 °C to 22 °C for bluegills produced no change in toxicity of azinphos-methyl at the lower temperatures and a 2-fold increase at the higher temperatures. Yellow perch became substantially more susceptible with an increase in temperature; 96-hour $LC_{50}$'s decreased from 0.04 to 0.0024 mg/liter when temperature was increased from 7 °C to 22 °C. Variations in water hardness from 12 to 300 mg/liter produced no change in toxicity to scuds or fish. Alkaline solutions (pH 8.5 to 9.0) were slightly less toxic to fish than more acidic solutions (pH 6.5 to 7.5). Aqueous degradation from 1 to 3 weeks produced a 1.3- to 2-fold increase in 96-hour $LC_{50}$'s for Atlantic salmon and yellow perch. Atlantic salmon eggs were highly tolerant to poisoning (11-day $LC_{50}$ greater than 50 mg/liter). The susceptibility of yolk-sac fry equaled that of fingerlings. Time-independent $LC_{50}$'s ($TILC_{50}$) were 0.000 23, 0.000 29, and 0.000 32 mg/liter for Atlantic salmon, bluegills, and yellow perch, respectively. The $TILC_{50}$ is a statistical estimate of the toxicant concentration at which 50 percent of the test population would be expected to survive a long-term exposure. Cumulative toxicity indexes varied from 10.9 to 20.5, indicating a moderate to high degree of cumulative action (for an organophosphate).

The cumulative toxicity index is the numerical ratio of the 96-hour $LC_{50}$ to the $TILC_{50}$ for a chemical. This ratio can serve as an estimate of the cumulative action of a toxicant. For example, a ratio of 2:1 suggests little cumulative action. Adelman et al. (1976) found that 0.000 51 mg/liter but not 0.000 33 mg/liter drastically reduced egg production of the fathead minnow, but caused no other apparent adverse effects.

## Carbofuran



Carbofuran

Carbofuran is a broad-spectrum carbamate insecticide. It has major registrations for a wide variety of soil and foliar insect pests in numerous agricultural crops. Forestry uses include control of seed and cone insects in nurseries and seed orchards and as a root dip at time of planting (see footnote 3).

### Behavior in the Environment

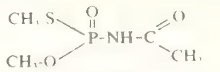
Carbofuran is soluble to 700 mg/liter in water (25 °C) and has a vapor pressure of $2x10^{-5}$ mmHg (33 °C). The moderately low vapor pressure suggests low volatility from soil. Tu and Miles (1976) classed carbofuran as slightly volatile (the least volatile group) in soil at 20 °C. Carbofuran, like the other carbamate insecticides, disappears rapidly from soil. Fuhremann and Lichtenstein (1980) measured about 60- and 90-percent losses of carbofuran in 14 days from loam and sandy soils in which oats were germinated and grown. Caro et al. (1973) reported it disappeared from soil by apparent first-order kinetics with half lives ranging from 46 to 117 days. The reaction is likely mediated by both chemical and biological processes. Getzin (1973) reported half lives ranging from 3 to 50 weeks in different sterile and nonsterile soils. The loss was 7 to 10 times faster in alkaline soils (pH 7.9) than in acid or neutral soils (pH 4.3 to 6.5). Goring et al. (1975) included carbofuran in the "moderately persistent in soil" group of pesticides (half lives of 1.5 to 6 months). Sanborn (1974) did not detect a bioaccumulation of carbofuran in a multicomponent model ecosystem, although evidence of substantial degradation on tight binding appeared in all components. Additional specific data on carbofuran are lacking, but it is expected to behave similarly to other carbamate insecticides.

We did not find any published reports of carbofuran in forest waters. There are unconfirmed reports of carbofuran in surface and subsurface water draining from seed orchards on sandy soils in the southeastern United States. Its predominant pattern of use minimizes the likelihood that forestry uses of this insecticide will result in its residues entering forest surface waters in the West.

### Toxicity

Data on carbofuran toxicity are limited. It is considerably more toxic than the other carbamate insecticides (such as carbaryl). Johnson and Finley (1980) summarized the work carried out at the National Fish Research Laboratory, Columbia, Missouri. Salmonids had 96-hour $LC_{50}$'s of 0.164 to 0.560 mg/liter, cyprinids (fathead minnow) 0.872 mg/liter, and percids (yellow perch) 0.147 mg/liter. Parrish et al. (1977) calculated the 96-hour $LC_{50}$ of carbofuran to the sheepshead minnow to be 0.386 mg/liter. Adults exposed to concentrations equal to or greater than 0.049 mg/liter showed significantly greater mortality than control fish during the 131-day study. Hatching success from eggs spawned by fish exposed to 0.049 mg/liter was significantly less than for eggs of nonexposed fish. Mortality of fry hatched from eggs spawned by fish exposed to 0.23 and 0.049 mg/liter was significantly greater than control fry mortality. Davey et al. (1976) noted that carbofuran was the least toxic of five rice-field pesticides to the mosquitofish and green sunfish. Klaassen and Kadoum (1979) found that carbofuran was present in the water and mud of a farm pond only immediately after application of 0.025 mg/liter. No adverse effects were observed.

## Acephate



Acephate

Acephate is a moderately persistent, organophosphate insecticide. It is used to control defoliating insects on several agricultural crops. In forestry, it is used to control seed and cone insects in seed orchards and the western spruce budworm in forest stands (1.5 kg/ha) (see footnote 3).

### Behavior in the Environment

Willcox and Coffey[17] summarized the behavior and the toxicity of acephate. It is degraded in soil by microbial action. Chevron[18] reported that in soil from nine locations across the United States, acephate had a half-life ranging from 0.5 to 13 days when the soil was fortified to 1 or 10 mg/kg. The longest persistence was in a highly organic muck soil. In eight of the nine soils, the half-life ranged from 0.5 to 4 days. In the field, acephate residues declined from 5.5 mg/kg in 1 day to 0.03 mg/kg in 20 days and to less than 0.02 mg/kg 70 days after aerial application of 0.56 kg/ha in Pennsylvania. Soil residues were not detected after 3 days (Devine 1975). Szeto et al. (1978) reported a 90-percent decrease in acephate in 10 days in open forest floor, but only about a 70-percent decrease in semiopen or densely covered areas in a Pacific Northwest forest. No residues were detected 30 days after application.

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[17] Unpublished report, "Environmental impact of acephate insecticide (Orthene)," by H. Willcox III and T. Coffey, Jr., U.S. Dep. Agric., For. Serv., State and Priv. For., For. Insect and Dis. Manage., Northeast. Area, Upper Darby, Penn., 1977.

[18] Unpublished report, "The impact of Orthene on the environment," prepared by Chevron Chem. Co., Richmond, Calif., 1973.

In laboratory studies, acephate (freshly added) was readily leached in soil. Aged soil residues are much less mobile. The short persistence of acephate in biologically active soils is believed to minimize the likelihood of significant movement to ground water. According to Chevron (see footnote 18) acephate is hydrolyzed slowly in water (half-life at 21 °C: 46 days at pH 7.0, 55 days at pH 5.0, and 16 days at pH 9.0). In tests conducted to determine if acephate would be moved by runoff water, residues were found in both runoff water and associated soil particles. Sediments and submerged vegetation will also absorb acephate, but the residue levels decline rapidly.

Flavell et al. (1977) summarized the results of aquatic monitoring of pilot-scale applications of acephate to control the western spruce budworm in three, 405-ha blocks in Montana in 1976. Stream water collected the day of application from five streams in the treated areas contained acephate residues that ranged from 0.003 to 0.961 mg/liter. The average peak concentration for all five streams was 0.466 mg/liter (only one sample of the 69 collected in this study contained a concentration greater than 0.5 mg/liter). Rapid reduction in concentration occurred, typically 10-fold in 2 to 6 hours. Residues averaged 0.065 mg/kg (range 0.026 to 0.139 mg/kg) in fish and 0.036 mg/kg (range 0.0 to 0.107 mg/kg) in insects.

Rabeni and Gibbs[19] found 0.135 and 0.113 mg/liter acephate in two streams 1 hour after application of 0.56 kg/ha. After 1 day, these levels were reduced to 0.013 and 0.065 mg/liter. No residues were found in four species of fish or in bottom sediments from a pond 2 weeks after treatment with acephate at 0.56 kg/ha (Bocsor and O'Connor 1975).

Sanborn (1974) reported acephate did not accumulate in algae, clams, crabs, Daphnia, Elodea, mosquitofish, or snails in a model ecosystem that had both terrestrial and aquatic components. The acephate was applied at 1.12 kg/ha to the terrestrial portion of the system. The data also indicate more than 95-percent decomposition of acephate in the system in 33 days. Chevron (see footnote 18) reported acephate applied to achieve 0.1 mg/liter in water was not detected 6 weeks later.

Bluegills were continuously exposed to 1.0 or 0.01 mg/liter acephate ($^{14}$C-labeled) for 35 days, and tissue samples analyzed periodically to determine the rate and extent of $^{14}$C-residue accumulation. After the exposure period, the fish were transferred to untreated water for 14 days.[20] The maximum tissue concentration of radio-labeled residues in the edible portion was about 10 times the concentration in water. Upon transfer to uncontaminated water, fish exposed at both levels eliminated more than 50 percent of the residues in the edible portion within 3 days. These data indicate a low potential for bioaccumulation.

## Toxicity

The effects on stream fishes and invertebrates of an operational spraying of acephate to suppress spruce budworm were investigated by Rabeni and Stanley (1979). Acephate reached its maximum concentration of 0.14 mg/liter in North Brook and

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[19] Unpublished report, "The impact of Orthene, a spruce budworm insecticide, on aquatic macroinvertebrates in Maine, 1977," Rep. NA-FR-7, by C. F. Rabeni and K. E. Gibbs, U.S. Dep. Agric., For. Serv., Northeast. Area, Broomall, Penn., 1979.

[20] Unpublished report, "Exposure of fish to $^{14}$C-labelled Orthene: accumulation, distribution and elimination of residues," by B. O. Sleight, Bionomics Inc., Wareham, Mass., 1972.

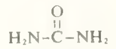
0.113 mg/liter in South Brook within an hour of spraying, and residues remained in streamwater for at least 2 days. The authors concluded that acephate caused relatively minor, short-term perturbations to the stream ecosystem (drift of macroinvertebrates increased; the standing crop of most invertebrates remained unchanged; brain AChE activity was depressed in suckers, but not in trout or salmon; and brook trout altered their diet, but growth was not affected). The authors drew these conclusions because the effects observed were either transitory or were not adverse. If the streams were adversely affected by spray drift, it was not detected by the methods used.

Willcox and Coffey (see footnote 17) summarized the pertinent literature on environmental impacts of acephate insecticide. Acephate has an extremely low toxicity to fish (rainbow trout, 96-hour $LC_{50}$ of 1000 mg/liter); though more toxic for invertebrates, no affects to Plecoptera or Ephemeroptera were recognized after treatment at 0.56 kg a.i./ha in a Pennsylvania stream and pond. Chevron[21] reported 96-hour $LC_{50}$'s of acephate to various fish species from 1000 mg/liter for rainbow trout to 9550 mg/liter for goldfish.

Johnson and Finley (1980) reported 96-hour $LC_{50}$'s of 1100 mg/liter for rainbow trout exposed to the technical material (94 percent), but 730 mg/liter when the soluble powder (75 percent) was used. The 96-hour $LC_{50}$ for various invertebrates ranged from 9.5 mg/liter (Plecoptera) to 1000 mg/liter (Diptera larvae).

Woodward and Mauck (1980) suggested that acephate would be the most acceptable of five forest insecticides tested from the standpoint of impact on nontarget aquatic organisms. It was nontoxic to cutthroat trout, and the lowest concentration toxic to aquatic invertebrates was much higher than the concentrations that could be expected in postspray water residue.

## FERTILIZERS



$H_2N\text{-}\overset{\overset{\displaystyle O}{\|}}{C}\text{-}NH_2$

Urea

Nitrogen (as urea) is the element most commonly applied as a fertilizer in Pacific Northwest forests. Application rates vary, but are usually 168 to 224 kg/ha urea-nitrogen (Moore and Norris 1974). Bengtson (1979) reviewed the use of fertilizers in forestry.

### Behavior in the Environment

Urea is highly water soluble and is readily moved from surface deposits into the forest floor and soil. Hydrolysis to ammonium ion is usually complete in 2 weeks. Ammonium nitrogen may be adsorbed by humic substances, held as an exchangeable cation, incorporated by soil microorganisms, or taken up by forest vegetation. Usually, it is quickly distributed through the biomass and is cycled within the forest ecosystem (Moore and Norris 1974).

Fertilizer nitrogen may enter the aquatic environment by the same routes described for pesticides. The highest concentrations of urea result from direct application to stream surfaces. Mobilization in ephemeral stream channels and subsurface drainage are important routes of entry for urea transformation products, primarily from the riparian zone.

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[21] Unpublished report, "Orthene insecticide - technical information," prepared by Chevron Chem. Co., Richmond, Calif., 1976.

Although forest soils are excellent filters for plant nutrients, increased levels of various nitrogen species have been measured in several stream systems in Pacific Northwest forests. In one of the more intensive efforts, Moore (1970) measured the amounts and forms of nitrogen entering streams during and after aerial application of 224 kg/ha urea-nitrogen in a southwestern Oregon forest. Urea concentrations increased slowly and reached a maximum of 0.39 mg/liter urea-N 48 hours after application started. Ammonium-N increased slightly above background but did not reach 0.10 mg/liter. Nitrate-N reached a peak concentration of 0.168 mg/liter in 72 hours and was 0.140 mg/liter at the end of 2 weeks. Nitrite-N was not detected. Only 0.01 percent of the nitrogen applied to the watershed was found in the stream up to 15 weeks after application.

Low streamflow because of limited precipitation in summer and fall resulted in essentially no loss of applied nitrogen during the next 24 weeks. Early storm activity in November brought the soil moisture back to maximum storage capacity, and in December the nitrate-N concentration in samples for the fertilized watershed reached a second peak of 0.177 mg/liter. Both streamflow and nitrate-N levels remained high through December and January, resulting in the loss of an additional 23.8 kg applied nitrogen. This is 92 percent of the total amount of fertilizer nitrogen lost during the 1st year.

Total loss of applied nitrogen from the 68-ha, fertilized watershed during the 1st year amounted to 25.85 kg (table 12). Over the same period, the total amount of soluble inorganic nitrogen lost from the 49-ha control watershed was 2.15 kg. Data for soluble organic nitrogen, total phosphorus, silica, and exchangeable cation content of the stream samples, including sodium, potassium, calcium, magnesium, iron, manganese, and aluminum, indicate that nitrogen fertilization had no apparent effect on loss of native soil nitrogen or other plant nutrients. Movement may have occurred in the soil profile, but no measurable change occurred in stream-water quality.

Table 12--Nitrogen lost from treated Watershed 2 and untreated Watershed 4, South Umpqua Experimental Forest, during the 1st year after application of 224 kilograms urea-N per hectare[1]

| | Urea-N | $NH_3$-N | $NO_3$-N | Total |
|---|---|---|---|---|
| | Kilograms N | | | |
| Watershed 2 | 0.65 | 0.28 | 27.09 | 28.03 |
| Watershed 4 | .02 | .06 | 2.07 | 2.15 |
| Net loss | .63 | .22 | 25.02 | 25.88 |
| Percent of total loss | 2.44 | .86 | 96.70 | 100.00 |

[1] From Moore (1971).

Similar data were reported by Moore (1975b) for several other monitoring studies conducted throughout the Douglas-fir region. Peak concentrations of urea-, ammonium-, and nitrate-nitrogen measured at each site monitored after fertilization are given in table 13. Monitoring varied from a few weeks after treatment to 6 or 7 months and, in a few studies, it continued at least a full year. Most sampling continued until the forms of nitrogen being measured had decreased to near pretreatment levels.

Increases in the concentration of urea-N ranged from very low to a high of 44.4 mg/liter. These increases were almost entirely because of direct application to surface water, and the peak concentration reached is directly proportional to the amount of open surface water in the treated unit. The high peak concentrations of urea-N measured in Dollar Creek and

Table 13--Peak concentrations of nitrogen in stream samples after forest fertilization with urea in Alaska, Idaho, Oregon, and Washington[1]

| Study site | Rate of application | Date of application | Treated area | Concentration of nitrogen | | |
|---|---|---|---|---|---|---|
| | | | | Urea-N | $NH_3$-N[2] | $NO_3$-N |
| | kg N/ha | | Hectares | ------------ | mg/liter | --------- |
| Burns Creek | [3]56 | Oct. 1970 | 562 | 0 | 0 | 0.068 |
| Canyon Creek | 224 | Oct. 1969 | 1346 | 15.20 | -- | .80 |
| Coyote Creek | 224 | Mar. 1970 | 68 | 1.39 | .048 | .177 |
| Crabtree Creek | 224 | May 1969 | 230 | 24.00 | .080 | .25 |
| Dollar Creek | 224 | Apr. 1971 | 34 | 44.40 | .490 | .13 |
| Elochoman River | 224 | Nov. 1969 | 297 | 19.10 | -- | 4.00 |
| Fairchilds Creek | 224 | Apr. 1972 | 192 | 23.40 | .280 | .828 |
| Falls Creek | 213 | May 1970 | 263 | -- | 1.28 | 1.67 |
| Jackson Creek | 168 | May 1969 | 95 | .09 | .044 | .116 |
| Jimmycomelately Creek | 224 | Apr. 1970 | 49 | .71 | .040 | .042 |
| McCree Creek | 56 | Oct. 1970 | 513 | .62 | 0 | .210 |
| Mica Creek | 224 | Sept. 1972 | 47 | .30 | 0 | .28 |
| Mill Creek | 224 | Dec. 1969 | 228 | .68 | .12 | 1.32 |
| Nelson Creek | 224 | Apr. 1970 | 38 | 8.60 | .32 | 2.10 |
| Newaukum River | 168 | Sept. 1971 | 2463 | .26 | .008 | .438 |
| Pat Creek | 224 | Apr. 1972 | 243 | 3.26 | .079 | .388 |
| Quartz Creek | 224 | May 1972 | 51 | 1.75 | trace | .70 |
| Roaring Creek | 224 | Mar. 1972 | 267 | .76 | .040 | .210 |
| Row River | 168 | Oct. 1972 | 2630 | .13 | .022 | .044 |
| Skookumchuck River | 168 | Sept. 1969 | 191 | 2.63 | .026 | .085 |
| Spencer Creek | 224 | Nov. 1972 | 3108 | .37 | .123 | [4].005 |
| Tahuya River | 224 | Oct. 1972 | 1602 | 27.20 | 1.40 | 1.83 |
| Thrash Creek | [5]224 | May 1974 | 121 | -- | .06 | 1.88 |
| Three Lakes | 213 | May 1970 | 69 | -- | .13 | 2.36 |
| Trapper Creek | 224 | Apr. 1970 | 64 | .70 | .010 | .121 |
| Trout Creek | 224 | Mar. 1968 | 648 | 14.00 | .700 | .160 |
| Turner Creek | 224 | Mar. 1972 | 352 | 4.36 | .046 | .243 |
| Waddell Creek | 224 | Dec. 1969 | 600 | 2.48 | .340 | .99 |
| Wishbone Creek | 224 | May 1972 | 46 | .30 | 0 | .28 |

-- = data not available.

[1] From Moore (1975b).
[2] Includes both ionized ($NH_4^+$) and un-ionized ($NH_3$) ammonia-nitrogen.
[3] Applied as ammonium sulfate.
[4] In this study, no increase occurred in $NO_3$-N. Concentration given is background level.
[5] Applied as ammonium nitrate.

Fairchilds Creek were because of greatly expanded stream-drainage systems caused by spring runoff of snowmelt. A buffer strip was left along Fairchilds Creek, but the expanded system of small feeder streams still resulted in direct application of fertilizer to a much larger area of surface water than would normally occur.

The peak concentrations of urea-N did not persist for more than a few hours. Concentrations characteristically reached a peak the day of application and then decreased rapidly. Within 3 to 5 days after application, urea-N in the stream returned to pretreatment concentrations.

Ammonium-nitrogen levels also increased as a result of direct application of urea fertilizer to open water. Urea is readily hydrolyzed to ammonium-N in the stream system. Urea applied to forest floor and soil surfaces will not reach the stream, because it hydrolyzes rapidly to ammonium carbonate and is then held on cation-exchange sites in the soil and forest floor like any other ammonium salt.

Peak concentrations of nitrate-N in streams after forest fertilization ranged from no increase in Spencer Creek to a maximum of 4.00 mg/liter in a tributary stream of the Elochoman River. The concentration of nitrate-N in stream samples usually reaches a peak 2 to 4 days after spring application of fertilizer. Concentrations then decrease, but may remain above background for 6 to 8 weeks. Losses of applied nitrogen are very small because the maximum concentrations reached are generally below 1 mg/liter nitrate-N, and streamflow rapidly decreases with the onset of the dry summer season. About half of the applied nitrogen entering the stream during the first 30 days is from direct application and is measured as urea- and ammonium-N. The other half enters as nitrate. In early fertilization projects where buffer strips were either inadequate or not used, estimated total loss was between 2 and 3 percent of the applied nitrogen. In later projects, however, where direct application to open surface water was minimized by buffer strips along the main streams and tributaries, measured losses were less than 0.5 percent.

In monitoring studies where sampling has continued through the first winter after fertilization, additional peaks in the concentration of nitrate-N have been measured. These peaks usually coincide with intense winter storms, and the concentration drops sharply between them. Maximum concentrations measured were low and tended to decrease with each successive storm (Moore 1971).

Patterns of nitrate-N loss to streams after early fall (September, October) application of fertilizer are similar to those after spring application. Peak concentrations measured during winter storms may not be as high, however, because of less time during warm weather for conversion of nitrogen to nitrate. The initial peak in nitrate-N concentration also occurs after fertilizer application in November and December. Subsequent peaks during winter storms are similar to those in streams draining untreated areas. Additional losses as nitrate-N may occur the next winter, however.

## Toxicity

Ammonia is one of the toxic breakdown products of fertilizers. U.S. Environmental Protection Agency (1976) stated:

> Ammonia is a pungent, colorless, gaseous, alkaline compound of nitrogen and hydrogen that is highly soluble in water. It is a biologically active compound present in most waters as a normal biological degradation product of nitrogenous organic matter. It may also reach ground and surface waters through discharge of industrial wastes containing ammonia as a byproduct, or wastes from industrial processes using "ammonia water."
>
> When ammonia dissolves in water, some of the ammonia reacts with the water to form ammonium ions. A chemical equilibrium is established which contains un-ionized ammonia ($NH_3$), ionized ammonia ($NH_4^+$), and hydroxide ions ($OH^-$). . . . The toxicity of ammonia is very much dependent upon pH as well as the concentration of total ammonia. Other factors also affect the concentration of $NH_3$ in water solutions, the most important of which are temperature and ionic strength. . . .
>
> It has been known since early in this century that ammonia is toxic to fishes and that the toxicity varies with the pH of the water. . . .

> In most natural waters, the pH range is such that the $NH_4^+$ fraction of ammonia predominates; however, in highly alkaline waters, the $NH_3$ fraction can reach toxic levels. Many laboratory experiments of relatively short duration have demonstrated that the lethal concentrations for a variety of fish species are in the range of 0.2 to 2.0 mg/l $NH_3$, with trout being the most sensitive and carp the most resistant. Although coarse fish such as carp survive longer in toxic solutions than do salmonids, the difference in sensitivity among fish species to prolonged exposure is probably small. . . . The lowest lethal concentration reported for salmonids is 0.2 mg/l $NH_3$ for rainbow trout (Salmo gairdneri Liebmann, 1960). The toxic concentration for Atlantic salmon smolts, (Salmo salar) (Herbert and Shurben, 1965), and for rainbow trout (Ball, 1967) was found to be only slightly higher. Although a concentration of $NH_3$ below 0.2 mg/l may not kill a significant proportion of a fish population, such concentration may still exert an adverse physiological or histopathological effect (Lloyd and Orr, 1969, Smith and Piper, 1975). . . . Burrows (1964) found progressive gill hyperplasia in fingerling chinook salmon, (Oncorhynchus tshawytscha), during a 6-week exposure to a total ammonia concentration (expressed as $NH_4$) of 0.3 mg/l (0.002 mg/l $NH_3$), which was the lowest concentration applied.

Another breakdown product of fertilizers is nitrate. The U.S. Environmental Protection Agency (1976) has only a recommended standard rather than a mandatory standard because nitrate has long been considered almost nontoxic to fish. Westin (1974) reported a 96-hour medium tolerance limit ($TL_m$) of 5800 mg/liter nitrate for chinook salmon fingerlings and 6000 mg/liter for rainbow trout fingerlings. Few data are available on other life stages, but Kincheloe et al. (1979) reported on nitrate exposure to egg and early fry stages of chinook and coho salmon, steelhead, rainbow, and Lahontan cutthroat trout. They found that nitrate (sodium) was mildly toxic to the early life stages of several salmonids. Coho salmon eggs and fry were resistant to nitrate toxicity. Chinook salmon, rainbow, Lahontan cutthroat, and steelhead trout eggs and fry exhibited mortalities during exposure to nitrate concentrations as low as 5 mg/liter. A complication was Saprolegnia (fungus) infestations of the eggs. The authors believe that nitrate levels of 10 mg/liter (2 mg/liter nitrate-N) in surface waters of low total hardness would limit survival of some salmonid fish populations because of impaired reproductive success.

Ammonium fertilizers have also been used to enrich fish ponds to increase productivity (Swingle 1947, Boyd and Sowles 1978). The application of ammonium fertilizers can lead to losses of alkalinity (Hunt and Boyd 1981) that subsequently require addition of agricultural limestone or liming to neutralize the acidity.

Stay et al. (1979) studied the effects of fertilizing a second-growth Douglas-fir forest with 224 kg urea-N/ha. Although they found sharp increases of urea in the stream during fertilization because of direct application, all nitrogen forms returned to near background levels shortly afterward. A 2-month rainbow trout bioassay showed no mortalities that could be attributed to byproducts or contaminants of urea. Changes in benthic and drifting invertebrates could not be related to the fertilization project.

# FIRE RETARDANTS

Modern chemical fire retardants are a complex mixture. The most abundant constituent (responsible for the fire-retardant action) is diammonium phosphate (Phos-Chek products), ammonium sulfate (Fire-Trol 100), or ammonium polyphosphate (other Fire-Trol products). Numerous other constituents are in the formulations applied in the field, however (tables 14 and 15). The behavior and impact of chemical fire retardants have not been extensively studied. Douglas (1974) reviewed this topic, Van Meter and Hardy (1975) conducted an initial simulation study of retardant distribution in streams, and C. W. George reviewed the literature on retardant toxicity to aquatics (see footnote 2).

The principal toxic ingredient of the chemical fire retardants currently in use is believed to be an ammonium salt (in the form of un-ionized ammonia, $NH_3$) (see footnote 2). A recent analysis, however, suggested that photolysis of the ferrocyanide in several Fire-Trol retardant formulations may lead to production of sufficient cyanide to be the primary toxicant in these products.[22/]

## Behavior in the Environment

The behavior of ammonium and ammonia in the environment is similar to that of the nitrogen derived from the hydrolysis of urea described in the previous section on urea fertilizer. Fire-Trol 931L and 934L are also ammonium-based fire retardants, but they contain ferrocyanide as a corrosion inhibitor. According to Burdick and Lipschuetz (1948, quoting Baudish and Bass 1922), ferrocyanide solutions "are decomposable to some extent under the influence of light" (sunlight). The product of photolysis is cyanide:

$$Fe(CN)_6^{-4} \text{ yields } Fe(CN)_5^{-3} + CN^- .$$

The $CN^-$ then reacts with water: $CN^- + H_2O$ yields $HCN + OH^-$, in an equilibrium reaction that is strongly pH dependent. $CN^-$ is relatively low in toxicity to aquatic species but HCN is quite toxic (analogous to the difference between $NH_4^+$ and $NH_3$). At pH 9.3, about half the cyanide will be HCN and half $CN^-$ (D'amore and Bellorno 1958). The environmental significance of this reaction was brought to light by a fish kill in New York in 1948. The fish kill extended over 12 miles of river and was associated with industrial discharge of ferrocyanides and ferricyanides (Burdick and Lipschuetz 1948). Investigators showed that the ferrocyanide and ferricyanide concentrations were below those generally accepted as lethal.

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[22/] Unpublished draft environmental assessment report, "Toxicity and environmental effects of fire retardant chemicals," prepared by U.S. Dep. Agric., For. Serv., Pac. Northwest Reg., Portland, Oreg., 1979.

Table 14--Typical composition of some chemical fire retardants[1]

| Chemical name | Empirical formula | Percent by weight in dry powder or liquid concentration | Parts per million in mixed retardant |
|---|---|---|---|
| Phos-Chek XAR,[2] Monsanto | | | |
| Diammonium phosphate | $(NH_4)_2HPO_4$ | 85-90 | 1.02-1.08x$10^5$ |
| Modified polysaccharide | -- | 5-10 | 6,000-12,000 |
| Iron oxide | $Fe_2O_3$ | 0-1 | 0-1,200 |
| Corrosion inhibitors: | | | |
| Soluble salt of-- | | | |
| Silicofluoride | $SiF_6^{-2}$ | .25-.58 | 300-700 |
| Thiosulfate | $S_2O_3$ | .01-5 | 1,200-6,000 |
| 2-Mercapto-benzothiazole | $C_6H_4SCSH:N$ | .0005-2 | 600-2,400 |
| Flow conditioner (insoluble) | -- | 2-4 | 2,400-4,800 |
| Phos-Chek 259R-(1.14 lb/gal), Monsanto | | | |
| Diammonium phosphate | $(NH_4)_2HPO_4$ | 92 | 111,000 |
| Modified polysaccharide | -- | 2.5 | 3,000 |
| Iron oxide | $Fe_2O_3$ | .75 | 902 |
| Corrosion inhibitors: | | | |
| Soluble salt of-- | | | |
| Silicofluoride | $SiF_6^{-2}$ | 1.47 | 1,768 |
| Thiosulfate | $S_2O_3$ | .71 | 854 |
| 2-Mercapto-benzothiazole | $C_6H_4SCSH:N$ | .20 | 241 |
| Flow conditioner (insoluble) | -- | 2.0 | 2,405 |
| Phos-Chek 259R-(1.6 lb/gal), Monsanto | | | |
| Diammonium phosphate | $(NH_4)_2HPO_4$ | 92 | 148,000 |
| Modified polysaccharide | -- | 2.5 | 4,024 |
| Iron oxide | $Fe_2O_3$ | .75 | 1,207 |
| Corrosion inhibitors: | | | |
| Soluble salt of-- | | | |
| Silicofluoride | $SiF_6^{-2}$ | 1.47 | 2,366 |
| Thiosulfate | $S_2O_3$ | .71 | 1,143 |
| 2-Mercapto-benzothiazole | $C_6H_4SCSH:N$ | .20 | 322 |
| Flow conditioner (insoluble) | -- | 2.0 | 3,219 |

Table 14--Typical composition of some chemical fire retardants[1], continued

| Chemical name | Empirical formula | Percent by weight in dry powder or liquid concentration | Parts per million in mixed retardant |
|---|---|---|---|
| Fire-Trol 100,[3] Chemonics | | | |
| Ammonium sulfate | $(NH_4)_2SO_4$ | 62 | 169,000 |
| Attapulgite clay | -- | 36 | 90,000 |
| Iron oxide | $Fe_2O_3$ | 1 | 2,500 |
| Corrosion inhibitors: | | | |
| Soluble salt of-- | | | |
| Dichromate | $CrO_7^{-2}$ | 1 | 2,500 |
| Fire-Trol 931L,[4] Chemonics | | | |
| Ammonium polyphosphate (10-34-0) | -- | 93 | 249,000 |
| Attapulgite clay | -- | 4 | 10,700 |
| Iron oxide | $Fe_2O_3$ | 1-2 | 2,600-5,400 |
| Corrosion inhibitors: | | | |
| Sodium ferrocyanide | $Na_4Fe(CN)_6$ | 1-2 | 2,600-5,400 |
| A dye[5] | -- | -- | -- |
| Fire-Trol 934L, Chemonics | | | |
| Ammonium polyphosphate (10-34-0) | -- | 97.5-98 | 258,000 |
| Sodium ferrocyanide | $Na_4Fe(CN)_6$ | 1.5 | 3,900 |
| Surfactant and water[5] | -- | -- | -- |

-- = information not available.

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[1] From Chemical Economics Handbook, January 1978, Menlo Park, California, Phosphorus Products, Page L.

[2] U.S. Patent 3,024,100 (March 6, 1962), Corrosion-Inhibited Liquid Fertilizer Compositions, granted to Langguth and Seifter and assigned to Monsanto Chemical Company. U.S. Patent 3,342,749 (September 19, 1967), Corrosion-Inhibited Phosphate Solutions, granted to Handleman, Groves, and Langguth and assigned to Monsanto Company.

[3] U.S. Patent 3,196,108 (July 20, 1965), Fire Supressing Composition for Aerial Application, granted to Nelson and assigned to Arizona Agrochemical Corp. (now Chemical Industries).

[4] U.S. Patent 3,960,735 (June 1, 1976), Corrosion-Inhibited Polyphosphate Compositions, granted to Lacey and assigned to Early California Industries, Inc.

[5] The formulation and concentration of these compounds were furnished by Chemonics and are not included because of their proprietary natures.

Table 15 Concentration of specific ions in some chemical fire retardants (estimated from data in table 14)[1]

| Specific ion | Formula | Parts per million in mixed retardant |
|---|---|---|
| Phos-Chek XA, Monsanto: | | |
| Ammonium + ammonia[2] | $NH_3$ | 26,300-27,900 |
| Phosphate | $PO_4^{-3}$ | 73,000-77,700 |
| Silicofluoride | $SiF_6^{-2}$ | 300-700 |
| Thiosulfate | $S_2O_3^{-2}$ | 1,200-6,000 |
| Mercaptobenzothiazole (MBT) | $C_7H_5NS_2$ | 600-2,400 |
| Phos-Chek 259R (1.14 lb/gal), Monsanto: | | |
| Ammonium + ammonia[2] | $NH_3$ | 28,600 |
| Phosphate | $PO_4^{-3}$ | 79,800 |
| Silicofluoride | $SiF_6^{-2}$ | 1,768 |
| Thiosulfate | $S_2O_3^{-2}$ | 854 |
| Mercaptobenzothiazole (MBT) | $C_7H_5NS_2$ | 241 |
| Phos-Chek 259R (1.6 lb/gal), Monsanto: | | |
| Ammonium + ammonia[2] | $NH_3$ | 40,140 |
| Phosphate | $PO_4^{-3}$ | 112,000 |
| Silicofluoride | $SiF_6^{-2}$ | 2,366 |
| Thiosulfate | $S_2O_3^{-2}$ | 1,143 |
| Mercaptobenzothiazole (MBT) | $C_7H_5NS_2$ | 322 |
| Fire-Trol 100, Chemonics: | | |
| Ammonium + ammonia[2] | $NH_3$ | 43,600 |
| Sulfate | $SO_4^{-2}$ | 122,900 |
| Dichromate | $Cr_2O_7^{-2}$ | 2,500 |
| Fire-Trol 931L, Chemonics: | | |
| Ammonium + ammonia[2] | $NH_3$ | 30,300 |
| Phosphate | $PO_4^{-3}$ | 113,300 |
| Ferrocyanide | $Fe(CN)_6^{-4}$ | 1,800-3,800 |
| Fire-Trol 934L, Chemonics: | | |
| Ammonium + ammonia[2] | $NH_3$ | 31,370 |
| Phosphate | $PO_4^{-3}$ | 117,000 |
| Ferrocyanide | $Fe(CN)_6^{-4}$ | 2,720 |

Studies of ferrocyanide conversion to cyanide were carried out by Burdick and Lipschuetz (1948) in open vessels exposed to sunlight during May and October. Initial potassium ferrocyanide concentrations ranged from 1 to 100 mg/liter, and exposure time was 1 to 5 hours. The inconsistent results were attributed to varying light intensity and temperature. The highest percent-conversions were at the low concentrations (1 to 5 mg/liter of potassium ferrocyanide at time zero). The term percent-conversion means transformation of mg/liter potassium ferrocyanide to mg/liter cyanide. Some of the runs with the lower concentrations showed a 25-percent conversion of potassium ferricyanide to cyanide.

In a more closely controlled experiment comparing 1, 2, and 3 mg/liter of potassium (K) ferrocyanide, the percent-conversions ranged from 10 to 15 percent in 1 hour, followed by a decrease in cyanide values. The decrease is attributed to loss of HCN and recombination of reaction products. In any event, although the percent-conversions of K ferrocyanide to cyanide vary (mg/liter $K_4Fe(CN)_6$ to mg/liter $CN^-$), the maximum value is about 25 percent.

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[1] From table 2, Draft Fire Retardant Environmental Assessment, USDA Forest Service, Pacific Northwest Region, Portland, Oregon, undated, 157 p.

[2] The distribution of N between the ammonium and the ammonia forms is both temperature and pH dependent. See unpublished report, The Behavior and Impact of Chemical Fire Retardants in Forest Streams, by Norris, Hawkes, Webb, Moore, Bollen, and Holcombe, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, Corvallis, Oregon.

The amount of sodium ferrocyanide that could reach surface water can be calculated, given the following assumptions:

- Fire-retardant mixtures contain up to 5400 mg/liter $Na_4Fe(CN)_6$ (equivalent to 3800 mg/liter $Fe(CN)_6^{-4}$).
- Air drop covers an area 75 m by 20 m with the rate of deposition of 2 liters/$m^2$.
- A stream 3 m wide and 0.2 m deep runs through the middle and along the long axis of the drop zone.
- Retardant mixing with the stream is instantaneous.

Based on these assumptions, the concentration of $Fe(CN)_6^{-4}$ would be 38 mg/liter [or 65 mg/liter as $K_4Fe(CN)_6$]. In a small pond (1233 $m^3$ = 1 acre foot), the concentration would be 9 mg/liter $Fe(CN)_6^{-4}$ or 15.6 mg/liter $K_4Fe(CN)_6$.

At a 25-percent conversion factor for the photolysis of the ferrocyanide to cyanide with 90 percent as HCN, the corresponding values are more than 8 mg/liter HCN in the stream and 2 mg/liter in the pond.

HCN disappears from water with time, as indicated by the reports of Burdick and Lipschuetz (1948) and Doudoroff (1956). Although their studies were in the laboratory, we expect the same phenomenon in natural streams, especially where continual mixing allows HCN to be released at the interface of air with water.

The cyanide ion readily forms complexes with many metals, particularly the "d" block of the periodic table. This would probably be more of a factor in lowland streams than in upland forest waters, however, because of the incidence of these heavier metals. Reports of cyanide degradation in water are lacking; it has been shown, however, that degradation occurs in activated sludges and in nonsterile soil. In nonsterile soil, the carbon of $CN^-$ is oxidized to carbonate, and the N goes to $NH_3$.

In summary, if sodium ferrocyanide is deposited in streams through the use of fire retardants, some cyanide will be produced through photolysis. The concentration will obviously depend on the amount of ferrocyanide deposited in the stream, the light intensity after deposition, and the volume of the stream. The $CN^-$ will not pose a long-term hazard because of volatility losses, dilution, and perhaps complexing with metals.

Norris et al. (see footnote 2) conducted an extensive study of the entry, behavior, and impact of an ammonium-based fire retardant in forest streams in Oregon, Idaho, and California; the results of this study are summarized below.

The tests (where retardant was applied across streams at four western locations) showed that direct application of retardant to the surface of the stream produced detectable changes in stream-water chemistry for distances up to 1000 m downstream. The changes were of short duration and not important, either toxicologically or with respect to eutrophication downstream. The rate of application was low, however, and only a single application was made on each stream. The effects of rate of application, vegetation density in the streamside zone, and other factors on retardant levels in streams were examined in simulation studies.

The stream-chemistry studies showed that direct application to the stream surface was the primary source of retardant components in streams. Once these initial residues left the stream reach, only minor amounts of retardant entered from the streamside zone. Relatively narrow, untreated strips in the streamside zone were sufficient to virtually eliminate movement of retardant from the land to the stream. In the Norris et al. (see footnote 2) study where the retardant was applied parallel to the stream, the edge of the treated area was only 3 m from the stream at several points.

The principal chemical species found in the stream within the first 24 hours after application were ammonium nitrogen and total phosphorus. Ammonium is of primary importance because of its potential effects on aquatic species. Phosphorus may be important in downstream eutrophication. After 24 hours, nitrate and soluble organic nitrogen were the primary retardant components in the stream. These are transformation products of the diammonium phosphate in the retardant mixture. Both chemicals are low in toxicity and are natural components of aquatic ecosystems.

Leaching studies showed that use of fire retardant on sites adjacent to streams can result in the entry of nitrogen into the stream in measurable quantities and in a form toxic to fish. The probability of occurrence of toxic levels is low, however, and can be further minimized by avoiding use of ammonium-based fire retardants on shallow, rocky, poorly developed soils occurring on steep slopes that drain directly into stream channels.

The simulation studies used computer-aid mathematical techniques with a combination of real and generated data to: develop methods for predicting the amount (concentration) of retardant in streams at the time they receive direct application to the stream surface; develop methods for describing the dispersal of retardant in streams, both with time after application and distance downstream from the zone of application; and integrate these two techniques with data on retardant toxicity to fish to evaluate the effects of various types of retardant application in various types of streams on fish mortality.

These simulations suggest:

- Direct application of retardant to streams is likely to cause fish mortality.
- The magnitude of the mortality and the distance over which it occurs vary with characteristics of the application, the site, and streamflow.

Characteristics of the Application. The characteristics of application (assuming a constant pattern of distribution) include orientation of the line of flight to the stream, size of load dropped, number of loads dropped, and the timing and placement of subsequent loads relative to the first load. For instance, applying retardant perpendicular to a stream produces a much smaller zone of mortality than when its long axis is centered on the stream. If the rate of application is doubled over the same area, the zone of mortality increases by a factor of 10 or more. We did not simulate the effects of multiple loads or the timing and placement of subsequent loads on the mortality zone, but believe the effects of additional loads will be at least additive to the effects of the first load. Where the rate of application increases, substantial increases in the length of the mortality zone occur. The characteristics of the application can be controlled by the fire-control officer and the applicator to minimize impacts on the stream.

Characteristics of the Site. For a given retardant application, several characteristics of the zone of application are important in determining the length of the fish-mortality zone. These include the width and depth of the stream and the density of overstream vegetation (leaf-area index). Results of the simulation suggest that narrow, deep streams have a much shorter mortality zone than shallow, wide streams (assumes equivalent flow properties). Furthermore, the more dense the vegetation canopy over the stream, the less chemical will fall into the stream and the shorter will be the mortality zone. The characteristics of the site can be recognized and allowed for by the manager and the applicator, thus minimizing chemical entry into the stream.

Characteristics of Streamflow. Streamflow characteristics influence the length of the mortality zone by determining the degree and speed of mixing and dilution of retardant with downstream travel. Simulation results for streams of roughly equal gradient (steepness) show that a stream with a smooth, straight channel is likely to have a longer mortality zone than one with many pools and riffles. Pools and riffles cause the peak of retardant concentration to spread out, thus reducing the magnitude of exposure. The other streamflow characteristic of importance is the increase in stream discharge with distance downstream (because of the inflow of ground water and contribution from side streams). Increased stream discharge results in dilution of the retardant. Characteristics of streamflow can be recognized by the manager and taken into consideration when planning fire-control strategies to minimize stream impacts.

## Toxicity

Douglas (1974) stated that retardants appear to have their greatest ecological impact on aquatic ecosystems. Numerous fish kills have been reported but few have been documented (see footnote 2). The few studies on the effects of fire retardants on fish populations show varying results, mainly because of the multitude of conditions that may be encountered. Blahm (1979) demonstrated that commercial fire retardants were toxic to juvenile coho salmon and rainbow trout and attributed the mortality to ammonia in the retardants. He noted that increasing the pH of diluent waters from 7 to 8 increased the toxicity. McKee and Wolf (1971) noted that ammonia concentrations as low as 0.3 mg/liter were lethal to trout fry and 75 mg/liter was extremely lethal to mature trout. Un-ionized ammonia ($NH_3$) has been reported to be the component of retardants likely to be toxic to fish and other organisms. The concentration of free $NH_3$ in any of the retardant-water mixtures depends on the amount of $NH_4^+$ contained in the retardant and the pH of the retardant-water solution. Blahm et al.[23/] found that two species of juvenile salmonids exposed to four commercial fire retardants had 96-hour $TL_m$'s of 120 to 940 mg/liter.

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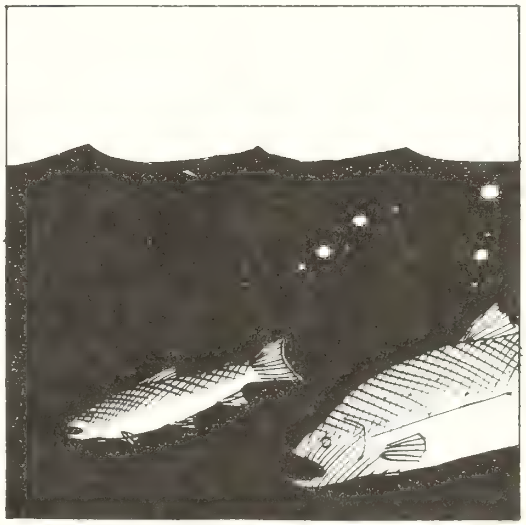
[23/] Unpublished report, "Effect of chemical fire retardants on the survival of juvenile salmonids," by T. H. Blahm, W. C. Marshall, and G. R. Snyder, Bur. Land Manage. Contract 53500-CT2-85(N), Natl. Mar. Fish. Serv., Environ. Field Stn., Prescott, Oreg., 1972.

Johnson and Finley (1980), investigating the toxicity of a Phos-Chek fire-retardant formulation, found that the 96-hour $LC_{50}$ for coho salmon and rainbow trout ranged from 160 to 320 mg/liter, but noted that yolk-sac fry of both species were more sensitive than fingerlings. Warm-water species were less sensitive than salmonids to two Phos-Chek formulations. The 96-hour $LC_{50}$ values for Phos-Chek 202 were 650 and 840 mg/liter for salmonids and fathead minnows, and for Phos-Chek 259 they were 300 and 350 mg/liter for salmonids and bluegills. A gammarid amphipod was the most sensitive, having a 96-hour $LC_{50}$ of 40 to 52 mg/liter, depending on the formulation tested.

The toxicological effects of sodium ferrocyanide, a corrosion inhibitor used in some retardant mixtures, may not have been adequately assessed (sodium ferrocyanide is presently used in Fire-Trol 931-L and 934-L). Doudoroff (1976) stresses that the suitability of cyanide-polluted waters for aquatic life has to be expressed as a concentration of free cyanide or molecular HCN, not of total cyanide. Free cyanide concentrations from 0.05 to 0.01 mg/liter as CN have proved fatal to many sensitive fishes (Jones 1964), and levels above 0.2 mg/liter are rapidly fatal for most species of fish. A level as low as 0.01 mg/liter is known to have a pronounced, rapid, and lasting effect on the swimming ability of salmonid fishes (National Academy of Sciences-National Academy of Engineering 1973). Blahm (1979) performed comparative evaluations of toxicity for different retardants and concluded that Phos-Chek formulations were more toxic to salmonid fishes than were Fire-Trol compounds. The higher toxicity was believed to be a function of pH and ammonia toxicity; Phos-Chek formulations are more basic than Fire-Trol compounds. Blahm's relative toxicity values for the two compounds is valid only if Fire-Trol 931 is mixed at a 4:1 ratio for field application. When applied as 3:1 or 2:1 mixtures, Fire-Trol 931 may have a higher ammonium toxicity than Phos-Chek compounds. Additional tests are warranted, because Fire-Trol 931 and 934 could apparently be more toxic to aquatic life than other approved retardants, especially on sunny days.



# HAZARD ASSESSMENT

## HAZARD ASSESSMENT AT THE ORGANISM LEVEL

The toxicological risk (or hazard) of forest chemicals to anadromous fish may be manifested through direct action on the fish themselves or indirectly through action on fish-food organisms. One means of expressing toxic risks is the margin of safety, the ratio of the no-effect level to the actual exposure level. When the exposure is equal to the no-effect level, the margin of safety is one. Margins of safety less than one indicate the exposure level is greater than the no-effect level and suggest that a direct toxic effect is likely. The larger the margin of safety, the less likely toxic effects will occur.

What constitutes an adequate margin of safety is a matter of judgment for many pharmaceuticals, caffeine, alcohol, and other materials many humans encounter daily. The margins of safety are as low as 1.5 to 15, and margins of safety of less than 100 are common. Margins of safety of about 100 are commonly used in setting pesticide tolerances in food and feed. Where the species are extremely valuable or rare, a much larger margin of safety may be appropriate. These margins of safety usually assume long-term chronic exposure will occur. Some margin of safety is necessary because the toxicity testing done thus far may not have identified the "lowest" no-effect level, toxicity-testing conditions usually differ from field conditions, and individuals in the population differ in susceptibility.

Forest chemicals have been investigated mostly for lethal effects; sublethal effects, however, may occur at lower exposures than those that are lethal. Potential sublethal effects of forest chemicals on salmonids include effects on growth, behavior, reproduction, resistance to stress, migration, biochemistry, and physiology. Picloram, 2,4-D, and DDT have been observed to cause reductions in fish growth in the field and laboratory (Warner and Fenderson 1962, Cope et al. 1970, Woodward 1976). Several types of behavior (for example, learning, swimming, temperature preference, predator avoidance) have been shown to be altered by exposure to pesticides (Ogilvie and Anderson 1965; Warner et al. 1966; Anderson 1968, 1971; Anderson and Peterson 1969; Hatfield and Anderson 1972; Hatfield and Johansen 1972; Symons 1973, 1977). Both DDT and 2,4-D have been demonstrated to cause decreased reproductive success in fish (Macek 1968, Wilbur and Whitney 1973). Diquat and picloram caused migratory inhibition in coho salmon smolts in coastal streams of Oregon (Lorz et al. 1979). Many studies have demonstrated biochemical or physiological change in fish after exposure to pesticides (Weiss and Gakstatter 1964; Grant and Mehrle 1970; Wildish et al. 1971; Hiltibran 1972a, b). One of the best documented biochemical effects of a forest chemical is the inhibition of AChE activity by organophosphates (Williams and Sova 1966). Scientists are aware of many potential sublethal effects of forest chemicals; however, data on sublethal effects are scarce and a large portion of the available information pertains to organochlorines, particularly DDT. The no-effect levels for sublethal effects of forest chemicals are most likely to be much lower than for acute or chronic toxicities. Our lack of knowledge prevents hazard assessment of forest chemicals for sublethal effects and forces us to use margins of safety; increased research on sublethal effects may allow us to better evaluate the potential effects of forest chemicals on anadromous salmonids.

Organisms can exhibit numerous kinds of responses when exposed to toxic chemicals. Survival, growth, reproductive success, and behavior characteristics are probably the most important, but the bulk of the aquatic toxicology literature reports only survival for short-term acute exposure in the water. Although this deficiency in the data base is obvious, fortunately in forest aquatic systems short-term acute exposures predominate, if exposure occurs at all. Thus, we can use toxicity data on survival of fish (or other more sensitive organisms) to approximate a no-effect level for short-term exposure.

We have selected a concentration of 0.1(96-hour $LC_{50}$) as the no-effect level for survival after brief acute exposures to peak concentrations of forest chemicals. This value is a little more conservative than the 0.1 of the 48-hour $LC_{50}$ tentatively suggested by the Aquatic Life Advisory Committee (1955). Some have treated this application factor almost as an immutable constant, but others have attacked it as an oversimplification. Tarzwell (1966) pointed out that 0.1 toxic units is a concentration that has been used successfully for the safe disposal of some wastes, when firm information was lacking. Sprague (1971) argued that no single value could be expected to fit all types of pollution. In his review of sublethal and "safe" concentrations, Sprague (1971) noted that a number of application factors were recommended but, in general, the accepted maximum levels are 0.1 or 0.05 toxic units for nonpersistent pollutants and 0.1 or 0.01 toxic units for persistent chemicals and pesticides. The National Academy of Sciences-National Academy of Engineering (1973) Water Quality Criteria also recommended the use of application factors not exceeding 0.1 of the 96-hour $LC_{50}$, where concentration of materials is nonpersistent or has noncumulative effects, to estimate "safe" concentrations of toxic wastes into receiving streams, unless specific application factors have been determined for a given material.

Relatively few data are available on the no-effect level for other types of responses, particularly for prolonged exposure to the chemicals we have discussed in this paper. The National Academy of Sciences-National Academy of Engineering (1973) Water Quality Criteria recommends that the concentration should not exceed 0.05(96-hour $LC_{50}$) at any time or place, nor should the 24-hour average concentration exceed 0.01 (96-hour $LC_{50}$) for persistent or cumulative toxicants.

Allison (1977) and Larsen et al. (1978) have investigated the relation of exposure duration, concentration, and periodicity of toxicants to toxicity, reproduction, and growth. These studies, using exposure units in conjunction with established toxicity data, may allow us to identify a "safe" level and thereby assess the environmental impact of variable-level, short-term pesticide exposure on the aquatic environment.

## Assessment of Acute-Toxicity Hazard

Numerous exposure values can be used in calculating margins of safety (table 16). We used the single highest instantaneous concentration we found in surveying the literature and a peak concentration of 0.02 mg/liter, which we believe is the maximum likely to occur if minimum buffer strips are used and some direct application to surface water occurs. We used these values with 0.1(96-hour $LC_{50}$) to calculate the margin of safety for survival to acute exposure (table 17). These calculations yield conservative estimates of the margin of safety because the instantaneous peak concentration in the field does not persist for the 96-hour period in the toxicity test and current "best management practices" in the use of forest chemicals will not produce exposure levels that approach the peak concentrations listed in tables 16 and 17.

Table 16--Integral of concentration-time curves for 48 hours for several pesticides and 192 hours for urea in forest streams after aerial application[1]

| Pesticide | Actual peak concentration | Integral for actual peak concentration | Integral for assumed peak concentration of of 0.02 mg/liter for pesticides and 7.02 mg/liter[2] for urea |
|---|---|---|---|
| | mg/liter | (mg/liter)hours | (mg/liter)hours |
| 2,4-D | 0.014 | 0.116 | 0.167 |
| Amitrole | .110 | .498 | .091 |
| Dicamba | .037 | .310 | .167 |
| Malathion | .040 | .074 | .037 |
| Carbaryl | .121 | .343 | .057 |
| Acephate | .471 | 1.708 | .072 |
| Urea[3] | 1.389 | 38.2 | 193 |
| Urea[4] | .700 | 19.4 | 195 |

[1] Based on figure 4.

[2] Mean peak concentration of 28 fertilizer-monitoring projects summarized by Moore 1975b.

[3] Based on figure 4G.

[4] Based on figure 4H.

Table 17--Estimated margins of safety for survival of salmon, trout, or other more sensitive aquatic species to "short-term" exposure to selected forest chemicals

| Forest chemical | Organism | 96-h LC$_{50}$ | No-effect level, acute exposure[1] | Highest observed exposure and margin of safety[2] | Margin of safety for 0.02 mg/liter peak concentration[3] | No-effect level, chronic exposure (48 h)[4] | Short-term chronic exposure (48 h)[5] | Margin of safety |
|---|---|---|---|---|---|---|---|---|
| | | mg/liter | mg/liter | | | (mg/liter)hours | (mg/liter)hours | |
| Herbicides: | | | | | | | | |
| 2,4-D-- | | | | 0.84 mg/liter | | | [6]0.334 | |
| Dimethylamine | Rainbow trout | 100 | 10 | 11.9 | 500 | 48 | | 144 |
| | *Daphnia* sp. | 4 | .4 | .5 | 20 | 1.92 | | 5.7 |
| | Glass shrimp | .15 | .015 | <.1 | .7 | .072 | | .2 |
| Butyl ester | Cutthroat trout | .9 | .09 | .1 | 4.5 | .432 | | 1.3 |
| | *Pteronarcella* sp. | 1.5 | .15 | .2 | 7.5 | .72 | | 2.2 |
| PGBE ester | Cutthroat trout | 1.0 | .1 | .1 | 5 | .480 | | 1.4 |
| | *Daphnia* sp. | 1.2 (48-h) | .12 | .1 | 6 | .576 | | 1.7 |
| | Glass shrimp | .4 | .04 | <.1 | 2 | .192 | | .6 |
| Picloram-- | | | | 2.0 mg/liter | | | [7].083 | |
| Technical | Cutthroat trout | 3.5 | .35 | .2 | 17 | 1.68 | | 20 |
| | *Pteronarcys* sp. | .048 | .0048 | <.1 | .2 | .023 | | .3 |
| Potassium salt | Cutthroat trout | 1.5 | .15 | <.1 | 7.5 | .72 | | 8.7 |
| Tordon 101[8] | Rainbow trout | 8.6 | .86 | .4 | 43 | 4.13 | | 50 |
| Atrazine | | | | .42 mg/liter | | | [9].668 | |
| | *Chironomus tenans* | .72 (48-h) | .072 | .2 | 3.6 | 3.46 | | 5.2 |
| | *Daphnia* sp. | 6.9 (48-h) | .69 | 1.6 | 34 | 3.31 | | 5.0 |
| | Bluegill | 6.7 (48-h) | .67 | 1.6 | 34 | 3.22 | | 4.8 |
| | Brook trout | 4.9 (48-h) | .49 | 1.2 | 24 | 2.35 | | 3.5 |
| MSMA-- | | | | .01 mg/liter | | | [10]-- | |
| Liquid formulation | Cutthroat trout | 100 | 10 | 1 000 | 500 | 48 | | [11]-- |
| | *Gammarus fasciatus* | 100 | 10 | 1 000 | 500 | 48 | | [11]-- |
| | Bluegill | 12 | 1.2 | 120 | 60 | 5.76 | | [11]-- |
| Plus surfactant | Bluegill | 49 | 4.9 | 490 | 245 | 23 | | [11]-- |
| Fosamine ammonium | | | | [12]-- | | | [9].668 | |
| | Coho salmon, fingerling | 5 361 | 536 | [11]-- | >10 000 | 2 573 | | 3 852 |
| | Rainbow trout, yolk sac | 528 | 52.8 | [11]-- | 2 640 | 253 | | 379 |
| Glyphosate-- | | | | 2.6 mg/liter | | | [9].668 | |
| Technical | Rainbow trout | 130 | 13.0 | 5 | 650 | 62.4 | | 93 |
| Liquid formulation | Rainbow trout, fingerling | 8.3 | .83 | .3 | 41 | 3.98 | | 6.0 |
| | Rainbow trout, swim-up fry | 2.4 | .24 | <.1 | 12 | 1.15 | | 1.7 |
| | *Daphnia* sp. | 3 | .3 | .1 | 15 | 1.44 | | 2.2 |
| Dinoseb | | | | [12]-- | | | [6].334 | |
| | Cutthroat trout | .041 | .004 | [11]-- | .2 | .019 | | <.1 |
| Insecticides: | | | | | | | | |
| Malathion | | | | .042 mg/liter | | | [13].037 | |
| | *Daphnia* sp. | .001 (48-h) | .000 1 | <.1 | <.1 | .000 5 | | <.1 |
| | *Pteronarcys* sp. | .01 | .001 | <.1 | <.1 | .004 8 | | .1 |
| | Coho salmon | .17 | .017 | .4 | .8 | .082 | | 2.2 |
| Carbaryl | | | | .121 mg/liter | | | [13].057 | |
| | *Daphnia* sp. | .006 (48-h) | .000 6 | <.1 | <.1 | .002 9 | | <.1 |
| | *Pteronarcys* sp. | .001 7 | .000 17 | <.1 | <.1 | .000 8 | | <.1 |
| | Coho salmon | 4.34 | .434 | 3.6 | 22 | 2.08 | | 36 |
| Azinphos-methyl | | | | [12]-- | | | [10]-- | |
| | *G. fasciatus* | .15 | .015 | [11]-- | .7 | .072 | | [11]-- |
| | *Pteronarcys* sp. | .001 9 | .000 19 | [11]-- | <.1 | .000 9 | | [11]-- |
| | Coho salmon | .006 | .000 6 | [11]-- | <.1 | .003 | | [11]-- |
| Carbofuran | | | | [12]-- | | | [10]-- | |
| | Coho salmon | .530 | .053 | [11]-- | 2.6 | .25 | | [11]-- |
| | Rainbow trout | .380 | .038 | [11]-- | 1.9 | .18 | | [11]-- |
| Acephate | | | | .961 mg/liter | | | [13].072 | |
| | *Pteronarcella* sp. | 9.5 | .95 | 1.0 | 47 | 4.56 | | 63.3 |
| | Cutthroat trout | 100 | 10 | 10 | 500 | 48 | | 667 |
| | Rainbow trout | 1 100 | 110 | 114 | 5 500 | 528 | | 7 333 |
| Fertilizer: | | | | | | | | |
| Urea | | | | 44.4 mg/liter | | | [13]193.0 | |
| Ammonia | | | | [14].014 mg/liter | | | [15].83 | |
| | Coho salmon | .2 | .02 | 1.4 | 1 | .096 | | .1 |
| Fire retardant: | | | | | | | | |
| Ammonia | | | | [16]1.30 mg/liter | | | [17]-- | |
| | Coho salmon | .2 | .02 | <.1 | 1 | .096 | | [11]-- |

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[1] 0.1(96-hour LC$_{50}$) is assumed to be the no-effect level for survival for short-term acute exposure.

[2] Single highest instantaneous concentration reported in text or in cited reference (some values are adjusted for registered rates of application in forestry) and corresponding margin of safety (no-effect level/exposure level).

[3] Margin of safety (no-effect level/exposure level) for assumed peak concentration of 0.02 mg/liter for pesticides, 7.02 mg/liter for fertilizer (urea), and 130 mg/liter for fire retardant.

[4] Integral of 0.01(96-hour LC$_{50}$) concentration-time curve for 48 hours.

[5] Integral of concentration-time curves in figure 4, assuming a peak concentration of 0.02 mg/liter (see also table 16). A peak concentration of 0.02 mg/liter is assumed to be the maximum instantaneous concentration likely to result, based on operational monitoring. It assumes applications are made with minimum buffer strips and some direct application to the stream surface.

[6] From table 16, adjusted to 2.24 kg/ha application rate (based on data for 2,4-D, figure 4A), and peak concentration of 0.02 mg/liter.

[7] From table 16, adjusted to 0.56 kg/ha application rate (based on data for 2,4-D, figure 4A), and peak concentration of 0.02 mg/liter.

[8] Tordon 101 is a 4:1 mixture of 2,4-D and picloram. The risk-assessment calculations are done using exposure data for picloram only. See 2,4-D for relevant data on 2,4-D.

[9] From table 16, adjusted to 4.48 kg/ha application rate (based on data for 2,4-D, figure 4A), and peak concentration of 0.02 mg/liter.

[10] Data not available. Normal use is not expected to result in stream contamination.

[11] Margin of safety not calculated because no value for exposure is available.

[12] Data not available.

[13] From table 16, assumed peak concentration 0.02 mg/liter, except for urea which is based on assumed concentration of 7.02 mg/liter.

[14] From table 13, assumes 1-percent un-ionized ammonia (25 °C, pH 7.5).

[15] Based on proportion of ($NH_3$ + $NH_4^+$) to urea, table 12, and 1-percent un-ionized ammonia (25 °C, pH 7.5).

[16] Assumes 1-percent ammonia in 130 mg/liter retardant in stream water, from Norris et al. (1978).

[17] No estimate because of high variability in patterns of retardant use. Applications directly into streams will produce levels of ammonia greater than 1 mg/liter.

## Assessment of Chronic-Toxicity Hazard

We calculated the margin of safety for survival from chronic exposure using the integral of the concentration-time curve for chemicals in forest streams with the integral of the concentration-time curve for exposure that is equal to 0.01(96-hour $LC_{50}$). This concept is based on the use of exposure units--that is, the integral of duration and level of exposure, as developed by Allison (1977) and Larsen et al. (1978). The derivation of each of these values follows.

Numerous data sets report the concentration of herbicides in forest streams. In an effort to find one that would be representative, we normalized the concentration data for three herbicides and shifted the time scale slightly to show the peak concentration (100 percent) occurring 3 hours after application (fig. 4a, b, and c). The data for both amitrole-T in Wildcat Creek and 2,4-D in Preacher Creek show an increase in concentration as a result of rain (approximately 0.7 cm at Wildcat Creek and 0.6 cm at Preacher Creek on the 1st day after application). The areas under the curves were measured to give a time-concentration expression [(mg/liter)hours] of contamination for the first 48 hours after application, using the actual peak concentration observed, and assuming an instantaneous peak concentration of 0.02 mg/liter (table 16). The latter value is our estimate of the maximum contamination level likely to result if minimum buffer strips are used and some direct application to surface water occurs (see related discussion in the chemicals in water section and U.S. Department of Agriculture, Animal and Plant Health Inspection Service 1980).

The results show reasonably good agreement among chemicals with 0.167 (mg/liter)hours for 2,4-D, 0.168 (mg/liter)hours for amitrole, and 0.91 (mg/liter)hours for dicamba. The higher value for dicamba reflects its longer than normal persistence. Based on this analysis, we decided to use the 48-hour time-concentration expression of exposure of 0.167 (mg/liter)hours derived from the 2,4-D data from Preacher Creek (fig. 4a) (adjusted for rate of application) for all the aerially applied herbicides in table 17. MSMA was excluded because it is not usually applied aerially, and the limited monitoring for MSMA has not shown measurable residues in forest streams. Use of the 2,4-D data for the other herbicides is reasonable because we believe the predominant processes of entry are drift, direct application to the stream surface, and mobilization in ephemeral stream channels shortly after application. These processes are largely mechanical and should not vary greatly among the aerially applied herbicides discussed in this paper.

Data for the concentrations of malathion, carbaryl, acephate, and urea (from fertilizer) in streams at various times after application were plotted, and the area under the curves was integrated in the same way as for the herbicides (fig. 4d-h, table 16). The normal patterns of use of azinphos-methyl and carbofuran (used for control of seed and cone insects) will not result in contamination of forest streams.

The no-effect level for survival from chronic exposure to each chemical is expressed as the integral (over 48 hours) of the time-concentration curve equivalent to 0.01(96-hour $LC_{50}$) for that chemical. These values are expressed as (mg/liter)hours for 48 hours, just as the exposure data from field studies are expressed. For example, the 96-hour $LC_{50}$ for carbaryl and coho salmon is 4.34 mg/liter and 0.01(96-hour $LC_{50}$) is 0.0434 mg/liter. Because the

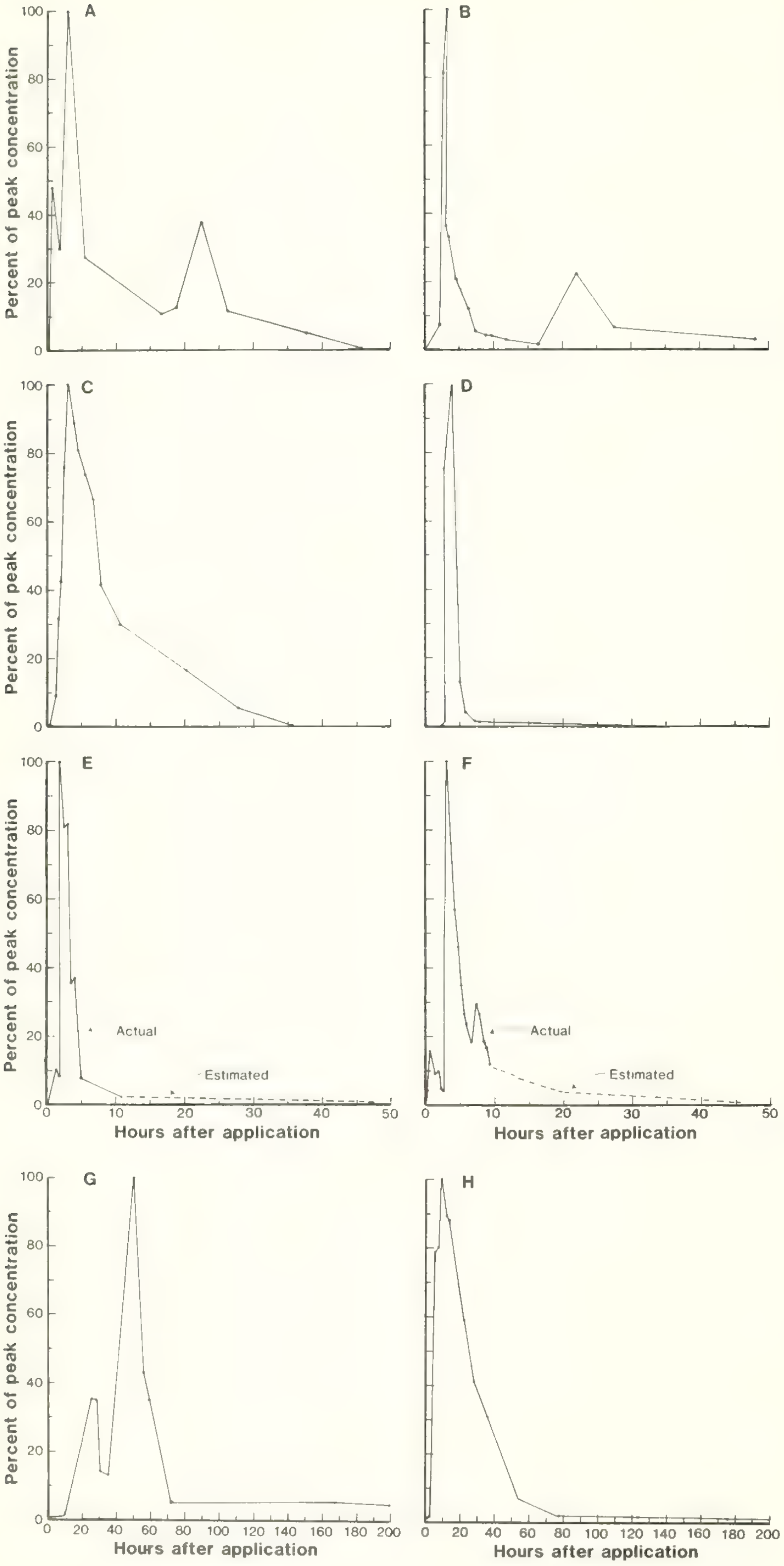

Figure 4.—Concentration of chemicals in forest streams at different times after aerial application. Concentration is expressed as a percentage of the peak concentration.

A. 2,4-D in Preacher Creek, with a partial stream buffer. Actual peak concentration was 0.0139 mg/liter after aerial application of 2,4-D at 1.12 kg/ha (from table 10, Fredriksen et al. 1975).

B. Amitrole in Wildcat Creek, with no stream buffer. Actual peak concentration was 0.110 mg/liter after aerial application of amitrole at 2.24 kg/ha (from table 10, Fredriksen et al. 1975).

C. Dicamba in Farmer Creek, with no stream buffer. Actual peak concentration was 0.037 mg/liter after aerial application of dicamba at 1.12 kg/ha (from fig. 2, Norris and Montgomery 1975).

D. Malathion in Hansel Creek, with no stream buffer. Actual peak concentration was 0.040 mg/liter after aerial application (from fig. 2, Tracy et al. 1977).

E. Carbaryl in Squilchuck Creek, with no stream buffer. Actual peak concentration was 0.121 mg/liter after aerial application at 1.12 kg/ha (from fig. 7, Bernhardt et al. 1978). Note projection of estimated concentration curve beyond 11 hours.

F. Acephate in Cabin Creek, with no stream buffer. Actual peak concentration was 0.471 mg/liter after aerial application at 1.12 kg/ha (from table 12, Flavell et al. 1977). Note projection of estimated concentration curve beyond 9.25 hours.

G. Urea in Coyote Creek, with no stream buffer. Actual peak concentration was 1.39 mg/liter after aerial application at 224 kg N/ha (as urea) (from table 1, Moore 1975b; and personal communication from D. G. Moore, For. Sci. Lab., Corvallis, Oreg., 1980). Note time scale is not the same as in figures 4A–F.

H. Urea in Trapper Creek, with 60-m stream buffer. Actual peak concentration was 0.7 mg/liter after aerial application of 224 kg N/ha (as urea) (from fig. 2, Moore 1975a). Note time scale is not the same as in figures 4A–F.

exposure level is constant over the 48-hour period we are interested in, the integral of the time-concentration curve is 0.0434 mg/liter x 48 hours = 2.08 (mg/liter)hours. The ratio of the no-effect exposure integral to the field exposure integral is the margin of safety (table 17).

We believe the margins of safety calculated for chronic exposure are conservative because the toxicity data are based on continuous exposure at the specified level, although we know from field data that the exposure is quite transitory. For instance, if we were to extend the period of evaluation from 48 hours to 30 days, the no-effect exposure integral would increase 15 times, but the field-exposure integral would not change because no further exposure occurs. Thus, the margin of safety would increase 15 times.

## HAZARD ASSESSMENT AT THE ECOSYSTEM LEVEL

Assessing the hazard to organisms rests on a reasonably adequate data base. But a disadvantage is that it focuses on individual organisms and does not take into account either time or space or the basic resiliency of ecosystems. For instance, our assessment for carbaryl indicates coho salmon will not be directly affected, but some individual invertebrates may be killed in a segment of a stream shortly after aerial application. It fails to recognize that some other individuals will survive (by avoidance or greater individual tolerance to the chemical) and that repopulation of the affected portion of the stream will occur (by migration from unaffected areas or hatching). In addition, it fails to recognize that the affected area is likely to be small because of efforts to avoid direct application to streams and because most treatments do not cover large, contiguous areas (some large insect-control projects may be an exception). The same area is not likely to be affected repeatedly because, over the course of any one timber rotation, more than three applications to the same area are rare and the time between repeat applications will usually be more than 1 year. As a consequence, we believe that the risk assessments in table 17 are conservative; the true margins of safety for anadromous fish from exposure to forest chemicals on the large watershed or ecosystem scale are larger than we have calculated.

# INDIRECT EFFECTS OF FOREST CHEMICALS

Effects of forest chemicals on aquatic organisms have been investigated for several decades, but these studies have generally been restricted to direct toxic effects. The use of herbicides, insecticides, fertilizers, and fire retardants may change the composition and production of terrestrial plants and invertebrates. Alteration of terrestrial vegetation and invertebrate communities may result in changes in allochthonous inputs into streams and in environmental factors such as light, temperature, water quality, sediment composition, and geomorphology. All of these factors are components of anadromous fish habitat as discussed by Reiser and Bjornn (1979). Land managers must be aware of potential indirect effects of forest chemicals on patterns and processes of stream ecosystems in the Pacific Northwest and Alaska.

## HERBICIDES

The following discussion of indirect effects of forest herbicides focuses on alteration of riparian vegetation adjacent to streams, rivers, and lakes. General aquatic processes that may be affected by terrestrial use of herbicides are described; documented studies of indirect effects of forest chemicals on aquatic systems are rare, however. Indirect effects of herbicides on aquatic communities have been observed as a result of mortality of particular components--for example, aquatic plants--and subsequent shifts in other components of stream ecosystems (Haven 1963, Smith and Isom 1967). They usually involve direct application of herbicide for aquatic weed control. In reviews of secondary effects of pesticides in aquatic systems, Hurlbert (1975) and Newbold (1975) viewed only the results of mortality to aquatic plants as the indirect effects of herbicides. Concentrations of herbicide in surface waters after forest application are much lower (less than 0.1 mg/liter) than those needed to control aquatic weeds (more than 2 mg/liter) (Norris and Moore 1971, 1976; National Research Council of Canada 1978; Norris 1978). Therefore, the effects that result from death of portions of biotic communities in streams are not pertinent to the subject of forest herbicides, except in unusual circumstances.

Herbicides may alter natural patterns of plant succession along streams. Herbicide application is intended to control nonconiferous trees and shrubs so that growth and development of commercial conifer species will be accelerated during the first few decades after timber harvest. In the following discussion, note that forest herbicides are applied to watersheds that have recently been logged. Therefore, we are comparing natural patterns of succession with patterns that are selectively constrained by human actions.

Plant succession after logging or burning generally goes through three stages: the weed stage, generally lasting less than 5 years; the shrub stage, roughly lasting from the 5th year through the 15th year; and the tree-dominated stage, which begins after about 10 to 15 years (Dyrness 1973; Franklin and Dyrness 1973). Tree communities are often dominated by deciduous trees, such as alder (*Alnus* spp.), bigleaf maple (*Acer macrophyllum* Pursh), or vine maple (*A. circinatum* Pursh), in the early stages of succession. Large shrubs, such as rhododendron (*Rhododendron macrophyllum* D. Don), *Ceanothus* spp., and salmonberry (*Rubus spectabilis* Pursh) are also major components of plant communities during this time. Between 20 and 60 years after cutting, coniferous species begin to dominate the tree communities.

In timber management, herbicides are often applied during the first decade after logging to control nonconiferous trees and shrubs. In essence, natural patterns of succession are altered because development and duration of early successional stages of trees and shrubs are reduced. Dominance of terrestrial vegetation is changed from herbs, shrubs, or hardwoods to conifers. This change in plant communities has many implications for stream communities in logged watersheds because deciduous vegetation differs greatly from coniferous vegetation in form, growth habits, timing of litterfall, and quality of organic matter produced. In addition, control of pioneer plant communities in the Pacific Northwest may have other long-term ecological implications because several pioneer species such as red alder (Alnus rubra Bong.) and Ceanothus are nitrogen fixers, and this region is generally nitrogen limited. Reduction of pioneer communities of nitrogen fixers may, therefore, alter nitrogen dynamics in watersheds treated with herbicides; few data from herbicide-treated areas are available, however (Tarrant and Trappe 1971).

Control of terrestrial vegetation may alter physical characteristics of the stream environment, such as streamflow, temperature, and light intensity. Immediately after reduction of nonconiferous plant biomass by herbicides, streamflow may increase because of reduced evapotranspiration (Hibbert 1967). Cutting of forests has been demonstrated to cause increases in both base flow and peak discharge (Hewlett and Hibbert 1961, Hornbeck et al. 1970, Harr 1977). Similar responses have been observed in watersheds treated with herbicides on rangelands (Ingebo 1971) and in northeastern forests (Mrazik et al. 1980). Herbicides are generally applied to watersheds that have recently been logged; therefore, herbicide use is not the primary cause of increased streamflow, but rather a factor that may extend this period of increased streamflow after deforestation. Increased base flow may be beneficial to many stream organisms, but increased peak flows may be detrimental. Reduction of streamside vegetation increases solar radiation reaching the stream channel and eliminates cover. Increases in solar radiation can increase summer stream temperature, depending on flow, gradient, and geomorphology (Brown 1969).

Alteration of the vegetative structure of watersheds may result in decreased streambank stability and increased erosion from hillslopes. The degree to which the vegetation and the rooting systems are altered determines the extent of sedimentation and channel modification, but the sedimentation rates of deforested watersheds are frequently more than double those of forested watersheds (Swanston and Swanson 1976). As previously mentioned, herbicides are applied to logged watersheds, which are much more erodible than forested watersheds. Therefore, herbicides must not be viewed as the primary cause of sedimentation but as a factor that retards the vegetative recovery of the watershed and may extend the period of increased sedimentation. Unfortunately, no studies have been published on the effects of herbicides on erosional patterns in logged watersheds. The detrimental effects of sedimentation and channel degradation on the structure and function of stream ecosystems have been documented extensively.[24]

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[24] Unpublished report, "Sediment and water quality: a review of the literature including a suggested approach for water quality criteria," by R. N. Iwamoto, E. O. Salo, M. A. Madej, and R. L. McComas, U.S. Environ. Prot. Agency, Reg. X, Seattle, Wash., 1978.

In sufficient concentrations, herbicides may directly affect aquatic primary producers (plants); indirect effects of herbicide applications may also alter primary producers in streams. As indicated earlier, increases in solar radiation may result from alteration of streamside vegetation and these increases may, in turn, cause greater rates of aquatic primary production (McIntire and Phinney 1965, Hansmann 1969, Gregory 1980). Such responses by aquatic primary producers have been observed after control of riparian vegetation by herbicides in rangelands of the Southwest (Smith et al. 1975). Temperature increases may also cause elevated rates of gross primary production in streams (McIntire 1966). Sedimentation from terrestrial systems that are influenced by herbicide use may cover benthic algal communities or scour algal cells from substrate surfaces, causing a reduction in standing crops of primary producers (Cordone and Pennoyer 1960, Chapman 1963, Nuttal 1972).

Primary production in streams may be stimulated by increased nutrient concentrations. Herbicide application has been observed to result in increased nitrogen inputs to streams (Sollins et al. 1981). A large amount of nitrogen was put into a stream after herbicide treatment of a watershed in New Hampshire; however, the rate of herbicide applied in this study was much greater than commonly used in forestry (Likens et al. 1970). Primary production in most Pacific Northwest streams has been demonstrated to be nitrogen limited (Thut and Haydu 1971, Gregory 1980); therefore, increases in nitrogen content of stream water as a result of herbicide application may stimulate rates of primary production.

Aquatic invertebrates may be affected by physical changes that result from herbicide application. Any increased sedimentation that may result from use of herbicides could have detrimental effects on communities of aquatic invertebrates through scour and alteration of habitat (Cummins and Lauff 1969, Burns 1972, Brusven and Prather 1974, Cederholm and Lestelle 1974). Temperature increases may result in increased growth and production of aquatic insects if the increases are slight; if stream temperatures exceed the optimum temperature for a particular species, however, the effects are negative.

Alteration of terrestrial vegetation by herbicides may influence communities of aquatic invertebrates. The initial increase in deciduous leaf fall into streams after herbicide application temporarily increases the food supply of aquatic invertebrates. In addition, the nitrogen content of this leaf material is greater than that of leaves that go through normal abscission (Jenson 1929, Sollins et al. 1981). Aquatic invertebrates attain faster growth and higher production on leaf material with high nitrogen content (Russell-Hunter 1970, Sedell et al. 1975). The duration of enhancement is short, however, because the conversion of the terrestrial stand to conifers results in a reduction of the more palatable deciduous material and an increase in less palatable coniferous material. Therefore, the quality of the food supply of detrital-feeding invertebrates decreases as the riparian zone returns to dominance by conifers.

The potential stimulation of aquatic primary production as a result of herbicide application could result in increased production of grazing insects. Grazers in streams are often food limited (McIntire and Colby 1978); therefore, increases in their food supply enhances their production. This enhancement of grazing invertebrates is gradually diminished as the developing coniferous stands shade the streams.

Aquatic predators, both invertebrate and vertebrate, could benefit from the enhancement of lower trophic levels. If production of grazing, collecting, and shredding invertebrates is increased as previously described, production of aquatic predators would also increase. Production of predators in streams in logged watersheds has sometimes been found to be greater than production in forested sections (Aho 1976, Erman et al. 1977, Hall et al. 1978, Murphy 1979). If herbicide treatment prolongs the stage of opened canopy after logging, this period of increased production could be extended. Release of the conifers may shorten the deciduous successional phase, however, and this phase may well be more productive for stream biota. Enhanced production of aquatic biota must therefore be viewed in the context of the normal patterns of ecosystem development.

Fish populations, especially salmonids, could also be detrimentally affected by herbicides. Salmonids prefer cold, clear streams; therefore, increased temperature and sedimentation from herbicide use may adversely affect salmonid populations. Sedimentation may reduce egg and fry survival (Neave 1947, Phillips 1964, Koski 1966)[25] and the quality of rearing habitat (Everest and Chapman 1972, Bjornn et al. 1974). Salmonids also require cover; streamside vegetation provides a major portion of this type of habitat (Lewis 1969, Hunt 1978). Reduction of streamside vegetation by forest herbicides would, therefore, adversely affect salmonid populations.

Herbicides may indirectly affect stream ecosystems either positively or negatively. The degree of impact is a function of the extent, level, patterns, and timing of applications. Evaluation of potential impacts of herbicides on stream ecosystems must incorporate all of these factors to achieve an accurate assessment.

## INSECTICIDES

Application of forest insecticides can indirectly influence stream ecosystems, primarily through the mortality of terrestrial or aquatic insects. These insects have relatively short life cycles (often 1 year or less); therefore, these communities can be expected to recover in less than 5 years. For this reason, indirect effects of forest insecticides on stream ecosystems may be more dramatic than those of herbicides, but they are of shorter duration.

Benthic algal commmunities in streams are frequently controlled by grazing invertebrates. The mortality of these aquatic invertebrates from insecticides may release the primary producers and result in higher standing crops. In streams in which insecticides were released directly, either intentionally or accidentally, standing crops of primary producers have been observed to increase from 2- to 20-fold (Barnley and Prentice 1958, Hynes 1961, Binns 1967, Chutter 1970). Similar responses have been observed in streams in watersheds that were treated with DDT for control of forest insects (Adams et al. 1949, Morgan and Kremer 1952, Webb and MacDonald 1958, Filteau 1959). Benthic algal communities are reduced as soon as invertebrate communities recover (Chutter 1970).

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[25] Unpublished annual completion report, "Embryo survival and emergence studies," by T. C. Bjornn, Proj. F-49-R-6, Job 6, Salmon-Steelhead Investigations, Embryo Survival and Emergence Studies, Idaho Fish and Game Dep., Boise, 1969.

Insecticides usually cause direct mortality of stream invertebrates as a result of toxicity. Those invertebrates that are resistant or have short generations may actually increase in number or size because of decreased competition, decreased predation, or increased algal food supply. In a Canadian stream that was inadvertently contaminated with gamma-BHC, populations of oligochaetes and midges increased (Hynes 1961). This increase was attributed to mortality of predators. An increase in small chironomids was observed after aerial application of DDT to forests in New Brunswick (Ide 1967). A decrease in predatory insects was also observed in this stream. A similar pattern of changes in invertebrate community structure was observed in streams within watersheds treated with carbaryl for control of spruce budworm (Courtemanch and Gibbs 1980).

Recolonization of streams affected by insecticides is dominated initially by invertebrates with short life cycles. Aquatic insects with life cycles of 1 year or more require several years to return to pretreatment populations. In addition to re-entry, survival, and reproduction, relative success of longer lived species is influenced by competition with established short-lived species. Predators tend to have long life cycles relative to other types of invertebrates; therefore, invertebrate communities do not return to previous levels of predation for several years. Full recovery of invertebrate communities therefore involves several complex interactions and may require 5 to 10 years.

Invertebrate predators have also been observed to increase after application of forest insecticides. Nigronia (dobsonfly) larvae populations increased in streams flowing through watersheds in Connecticut that were treated for spruce budworm (Hitchcock 1965). Other populations of predator insects, such as plecopterans, were observed to decrease during this period.

Contamination of streams with insecticides can cause increased drift of aquatic insects (Crouter and Vernon 1959) and increased entry of terrestrial insects (Warner and Fenderson 1962). These insects are ingested by drift-feeding fish such as trout and salmon. This may result in an indirect toxic effect on the fish. If the toxic effect is slight or nonexistent, this sudden increase in food may cause a brief acceleration of growth. Reduced competition resulted in greater growth of surviving brook trout after forest spraying of DDT in Maine (Warner and Fenderson 1962). Over the long term, however, the decrease in populations of benthic invertebrates will most likely result in decreased growth and production of fish populations. Recovery of fish populations is therefore determined by recovery of invertebrate communities.

## FERTILIZERS

Forests are often fertilized in the Pacific Northwest during several decades after logging. Urea is the most common fertilizer. It is quickly converted to ammonium or nitrate in the soil; therefore, nitrogen can enter streams in the form of urea, ammonium, or nitrate. Most of the urea that enters streams does so within the first 48 hours after application (Moore 1975a, b). After that, nitrogen enters streams primarily as nitrate. Fertilization generally results in nitrogen increases in stream water of 50 mg/liter or less, and these pulses of increased nitrogen last for about 1 year (Fredriksen et al. 1975; Moore 1975a, b).

As previously described, streams in the Pacific Northwest are commonly nitrogen limited. Primary production in such streams may be enhanced by increased nitrogen (Thut and Haydu 1971, Stockner and Shortreed 1976, Gregory 1980). The response to nutrient addition depends on light intensities because heavily shaded streams are light limited. Nutrient stimulation of primary production occurs only with sufficient light intensity (Gregory 1980). Because most fertilized watersheds are less than 40 years old, fertilization probably results in enhanced primary production in the streams.

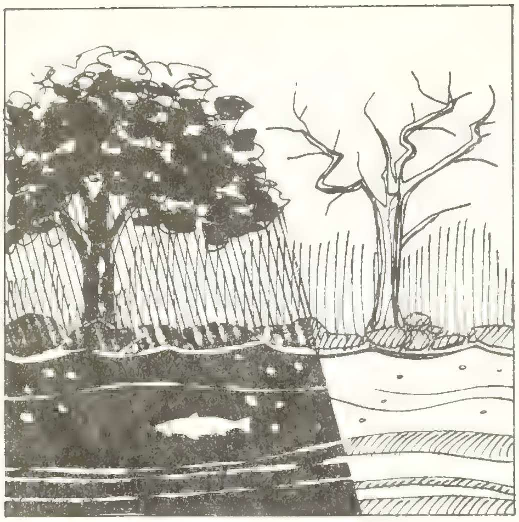
Increased primary production can result in greater production of consumers. Greater insect and trout production in open streams has been observed in many studies (Albrecht and Tesche 1961, Albrecht 1968, LeCren 1969, Mills 1969, Hall et al. 1978). Greater primary production in open reaches has been proposed as the cause for these increases. Fertilization could therefore result in greater production of trout and salmon. This increase would be limited to less than 5 years at best, but would be extended by repeated application of fertilizer at 5- or 10-year intervals.

## FIRE RETARDANTS

Chemical fire retardants such as ammonium sulfate, ammonium polyphosphate, or diammonium phosphate are used extensively in the Pacific Northwest for the suppression and control of forest fires. Fires often start on ridgetops, away from streams. As fires develop, they often sweep across streams and rivers, so direct entry of fire retardants into streams is possible.

Application of fire retardants usually results in increased concentrations of ammonia in stream waters (see footnote 2). These concentrations may range from 0.01 to 100 mg/liter of nitrogen. As discussed in the sections on herbicides and fertilizers, such nitrogen increases in streams of the Pacific Northwest have a great potential for stimulation of primary production and subsequent enhancement of higher trophic levels. Increased production of aquatic biota could be precluded if toxic effects occurred. Potential indirect effects on mortality of invertebrates or fish described in the section on indirect effects of insecticides would apply to fire retardants, if concentrations in streams were sufficient to cause mortality. In an experimental release of a fire retardant containing diammonium phosphate, no significant effects on benthic invertebrates or fish were observed (see footnote 2). The pulsed nature of the introduction may have prevented the stimulatory effect that might result when a large area is treated, with a longer release of nitrogen to the stream. Although most fire-retardant drops will occur along streams, retardants could be dropped in or around basins with longer hydrologic retention times than streams, such as oligotrophic lakes, bogs, or swamps. In such aquatic systems, the effect of fire retardants may be prolonged and exaggerated.

Included in the concept of using fire retardants to control forest fires is the basic consideration of the ramifications of controlling or not controlling fires. Fire is a natural reset mechanism in forests of the Pacific Northwest and a fundamental component of terrestrial plant succession. Human activities have duplicated many of the characteristics of fire in clearcutting and burning and have converted a major portion of the forests of the Pacific Northwest to a pioneer stage of succession. If fire retardants are not used and the land is allowed to burn, certain changes will occur in the terrestrial system and these will affect aquatic ecosystems. These effects were reviewed by Norris et al. (see footnote 2) and Swanston (1980). Briefly, potential effects of fire on anadromous fish habitat may include the following: decreased input of leaves and needles; increased input of wood; increased sedimentation; increased streamflow; increased solar radiation at the water surface; increased stream temperature; and increased nutrient inputs. The previous discussions of the effects of herbicides and fertilizers have dealt with these factors, and the potential indirect effects described would apply to watersheds that have been burned. Indirect effects of fire retardants must be weighed against those that would result if fires were not controlled, for accurately assessing the hazards of fire retardants.



## GENERAL PERSPECTIVES ON INDIRECT EFFECTS OF FOREST CHEMICALS

Forest chemicals have great potential for indirectly altering aquatic communities and anadromous fish habitat. Such changes must be examined within the context of all land-use practices. Forest chemicals are seldom used on watersheds that have not been previously altered; therefore, impacts of forest chemicals must be considered in relation to previous or simultaneous effects of other practices on habitat of anadromous fish.

Herbicides modify the natural patterns of terrestrial plant succession on logged watersheds so that the duration of early deciduous-dominated stages is reduced and coniferous vegetation develops more rapidly. The following characteristics of aquatic systems are influenced by the alteration of terrestrial succession: allochthonous organic inputs; tree and shrub canopy over the stream; stream chemistry; and sedimentation rates. These factors are major determinants of the structure and function of stream ecosystems and are affected by logging, with or without the use of herbicides. The basic effect of herbicides is to extend the early stages of watershed recovery, minimize intermediate stages, and accelerate development of coniferous stages. Potential indirect effects of herbicides on aquatic ecosystems must be therefore viewed within this successional framework.

Fertilizers, like herbicides, are applied to logged watersheds to stimulate production of vegetation. Nutrient inputs to streams from application of fertilizer may influence aquatic communities, particularly through stimulation of primary producers; however, these aquatic communities will have already been altered by the effects of logging. Fertilizers may indeed enhance many of the stimulatory effects of logging on aquatic primary producers. Fertilizers are usually applied after canopy closure to avoid stimulating growth of competing species and provide greater utilization by conifers. Fertilization at 5-year intervals could gradually increase nitrogen concentration in forest streams at base flow.

Fire retardants, unlike herbicides and insecticides, are generally applied while watersheds are being directly affected--in this case by fire. Fire has many impacts on anadromous fish habitat; these effects were reviewed by Swanston (1980). Indirect effects of fire retardant are generally limited to stimulation of primary production, and even that effect is greatly influenced by the fire itself through reduction of canopy over the stream.

Insecticides, more than any other forest chemical, may be applied to watersheds that are least influenced by human activities. Even with insecticides, the impacts of the chemical must be viewed in relation to effects on aquatic systems of insect damage to forests. These insect-related effects would be much less severe than the effects associated with logging or fire, but still must be incorporated into decisionmaking processes.

In assessing potential indirect effects of forest chemicals on anadromous fish habitat, land managers must consider the influence of protective measures (particularly buffer strips) on the patterns and processes of aquatic systems that have been described. Frequently, corridors along streams or around lakes are left unsprayed and the terrestrial communities and processes within these "spray buffer strips" may be practically identical to similar areas in untreated watersheds. Effects of chemical spraying would have to be transferred through such spray buffer zones and would therefore have much less impact on aquatic communities. In clearcut watersheds where buffer strips of uncut vegetation are left, the use of spray buffer strips would be even more effective in reducing potential indirect effects of forest chemicals. If buffer strips of uncut vegetation and no-spray zones are used in watershed management, many of the patterns of indirect effects of forest chemicals on stream ecosystems described in this chapter would not occur.

Forest chemicals are a major tool in managing our Nation's forests. Risks in the use of chemicals must be evaluated, however. Direct toxic effects of chemicals on aquatic organisms are major concerns; forest chemicals may have indirect effects on aquatic ecosystems at concentrations much lower than those observed to cause mortality. Potential effects of forest chemicals must be evaluated on the basis of four factors:

- Changes in aquatic communities caused by forest chemicals;
- Subsequent changes in other communities of aquatic organisms;
- Alteration of terrestrial systems that influence aquatic ecosystems; and
- Effects on patterns of recovery in watersheds that have already been altered by logging or fire.

Though few studies of indirect effects of forest chemicals on anadromous fish habitat are available to land managers, the perspectives presented in this paper will provide a basis for evaluating potential indirect effects and designing management systems to minimize them.

# RESEARCH NEEDS

The greater the amount and quality of information available on any subject, the more certain a decisionmaker can be of reaching correct conclusions about it. This fact and the desire to reach correct conclusions prompts scientists to prepare lengthy lists of research needs, many of which seem to be endless repetitions of earlier lists. All research needs are not equally important. We have attempted to focus attention on those gaps in knowledge that we believe have resulted in the greatest uncertainty in the information presented in the earlier part of this paper. We identify these gaps specifically. We believe they are discrete research areas that are small enough to be solved by a single scientist or a small group of scientists. No one area will require major long-term grants or funding programs, although in aggregate, the solution of these problems will require substantial effort. We present the list of research needs in the order the subjects appear in the paper.

## BEHAVIOR OF CHEMICALS IN THE ENVIRONMENT

- Quantify the role of buffer strips in influencing the concentration of forest chemicals in streams.

Research and practice have demonstrated that buffer strips reduce the entry of chemicals into forest streams, but the degree of protection provided by strips of different widths has not been quantified. Some relatively simple experiments are needed to show the degree of improvement that can be achieved with buffer strips of various widths.

- Determine the pattern of entry of atrazine, fosamine ammonium, glyphosate, and dinoseb herbicides, as well as fire retardants, into western forest streams under actual conditions of use.

Most of the research and monitoring of the entry of chemicals into streams, particularly in connection with operational application, were done when the phenoxy herbicides were the predominant forest chemicals. Consequently, few data are available on other forest chemicals. The lack of data is particularly acute for atrazine, fosamine ammonium, glyphosate, and dinoseb herbicides and fire retardants.

- Determine more precisely the fate of all forest chemicals in forest streams.

Almost no data are available on the distribution of chemicals among the various parts of western forest stream systems. The data used in our paper are mostly from laboratory studies or where the chemical in question was intentionally applied to ponds or slow-moving streams for aquatic weed control. Extensive work in this area is not needed, only enough to establish the degree to which concepts developed in other types of aquatic systems fit in aquatic systems used by anadromous fish.

## TOXICITY OF CHEMICALS TO AQUATIC SPECIES

- Determine the toxicity characteristics of the combinations of forest chemicals that are likely to be applied together.

Studies on the effects of combinations of chemicals (for example, picloram and 2,4-D) have generally been restricted to plants. Similar work with sensitive aquatic vertebrates and invertebrates is required to assess adequately the effects of combined chemicals.

- Characterize the interaction between concentration and duration of exposure among forest chemicals and the more sensitive aquatic species.

Most toxicity tests hold the concentration of chemical constant for a specified period (such as 24, 48, or 96 hours) and evaluate organism response soon afterward. Exposure of aquatic organisms in the field is typically to concentrations of chemical that increase to a peak within a few hours after aerial application and then decrease rapidly to much lower levels in a few hours. A relation needs to be established that will permit the use of the extensive existing toxicity data base (which was developed by using constant exposure methods) in evaluating the toxicological significance of field exposure data. In this paper, we used an integral of the time-concentration curve, but this approach has not been fully validated.

- Determine if the results of classical 96-hour exposure tests are adequate predictors of the long-term well-being of aquatic organisms.

Nearly all the toxicity testing on aquatic organisms has used short-term exposure and only short-term observation of effects. Research is needed to determine if long-term latent effects result from short-term exposure. Tests with a few chemicals and a few key species may be sufficient to establish this point. With a few notable exceptions, we do not believe that latent effects will develop from short-term exposure to most toxicants.

## INDIRECT EFFECTS OF FOREST CHEMICALS

- Quantify indirect effects of forest chemicals on aquatic organisms under field conditions.

- Determine sublethal effects of forest chemicals on aquatic organisms.

Research on these areas is critically needed before adequate conceptual frameworks can be developed for designing research to investigate indirect effects of forest chemicals under field conditions. Indirect effects on aquatic ecosystems will most probably involve several types of aquatic organisms; such effects, therefore, would be much more complex and subtle than direct toxic effects. Research must be tightly focused and properly timed to permit the observation of changes in aquatic communities. Because indirect effects may be caused by concentrations of chemicals much lower than lethal concentrations, further research on indirect effects of forest chemicals on aquatic ecosystems is required to assure safer use of chemicals in the forest environment.

# CONCLUSIONS

The use of forest chemicals can result in both direct and indirect effects on anadromous fish and their habitat. Direct toxic effects are those resulting from the exposure of fish to a chemical in water, food, or sediment. The potential for direct effects can be estimated, based on knowledge of the toxicity characteristics of the chemical and its movement, persistence, and fate in the environment.

The most important process by which chemicals enter streams is direct application, but drift from nearby treatment areas or units is also important. Mobilization of residues in ephemeral stream channels during the first storms after application is sometimes important. All three processes can be influenced by forest managers. Selection and orientation of spray units to avoid streams, and attention to the details of application to avoid drift, will minimize chemical entry into streams and thereby reduce the likelihood of direct toxic effects on stream organisms.

The margin of safety (no-effect level/exposure level) is a good index to the probability that the use of a specific forest chemical will result in direct effects on anadromous fish. The larger the margin of safety, the less likely direct effects will occur. Margins of safety of less than one indicate direct effects are likely to occur. We calculated the following margins of safety for fish, based on the maximum acute and short-term chronic exposures likely to occur in operational use of these chemicals:

|  | Margin of safety |  |
|---|---|---|
| Chemical | Acute | Short-term chronic |
| 2,4-D (PGBE ester) | 5 | 1.4 |
| Picloram (Tordon 101) | 43 | 50 |
| Atrazine | 24 | 3.5 |
| MSMA | 500 | [26]-- |
| Fosamine ammonium | 2640 | 379 |
| Glyphosate | 12 | 1.7 |
| Dinoseb | 0.2 | < 0.1 |
| Malathion | 0.8 | 2.2 |
| Carbaryl | 22 | 36 |
| Azinphos-methyl | [26]-- | [26]-- |
| Carbofuran | [26]-- | [26]-- |
| Acephate | 500 | 667 |
| Fertilizer | 1 | 0.1 |
| Fire retardant | 1 | [27]-- |

These margins of safety will be 5 to 10 times greater when streams are not included in areas to be treated, buffer strips are used, and full attention is given to the details of application to prevent drift and direct application to surface water.

Indirect effects are manifested through chemically induced changes in the density and species composition of aquatic and terrestrial plants and insects. These effects may include alteration of nutrient, sediment, and temperature characteristics of the water, and changes in cover, food, or some other environmental characteristic that is important to the well-being of anadromous fish. These changes have not been as thoroughly studied as the direct effects, but may be the most likely to occur.

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[26] Current pattern of use does not result in measurable residues of chemical in water; therefore, exposure is very small and the margin of safety is very large.

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[27] Margin of safety not calculated because no value for exposure is available.

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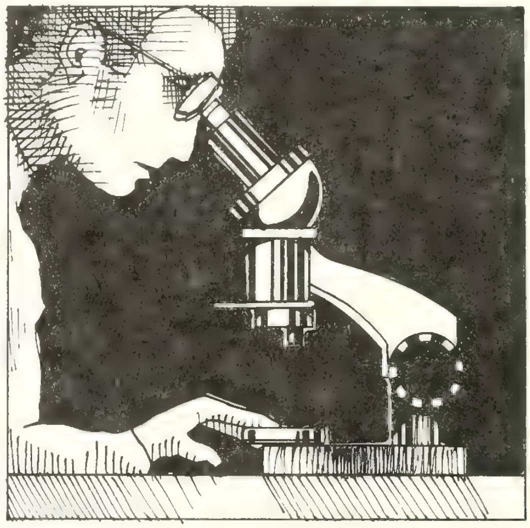

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# APPENDIX

Table 18--Common, chemical, and trade names of chemicals referred to in text and tables

| Common name | Chemical name | Trade name used in text |
|---|---|---|
| Fertilizer: | Urea | None |
| Fire retardants: | None | Fire-Trol 100<br>Fire Trol 931L<br>Fire-Trol 934L<br>Phos-Chek<br>Phos-Chek XAR<br>Phos-Chek 202R<br>Phos-Chek 259R |
| Herbicides: | | |
| 2,4-D | 2,4-dichlorophenoxyacetic acid (and various esters and salts) | None |
| 2,4,5-T | 2,4,5-trichlorophenoxyacetic acid | None |
| Amitrole | 3-amino-1,2,4-triazole | Amitrole-T |
| Atrazine | 2-chloro-4-ethylamino-6-isopropyl-amino-s-triazine | None |
| Dicamba | 3,6-dichloro-o-anisic acid | None |
| Dinoseb | 2-sec-butyl-4,6-dinitrophenol | None |
| DSMA | Disodium methanearsonate | None |
| Fosamine ammonium | Ammonium ethylcarbamoyl-phosphonate | Krenite |
| Glyphosate | N-phosphonomethylglycine | Roundup |
| MSMA | Monosodium methanearsonic acid | None |
| Picloram | 4-amino-3,5,6-trichloropicolinic acid (and various esters and salts) | Tordon 22K<br>Tordon 101 (also contains 2,4-D) |
| SDMA | Sodium dimethyl arsonate | None |
| Silvex | 2-(2,4,5-trichlorophenoxy)-propionic acid | None |
| Insecticides: | | |
| Acephate | O,S-dimethyl acetylphosphor-amidothioate | Orthene |
| Azinphos-methyl | O,O-dimethyl-S-[(4-oxo-1,2,3-benzotriazine-3-(4H)-yl)methyl] phosphorodithioate | Guthion |
| Carbaryl | 1-naphthyl-N-methylcarbamate | Sevin<br>Sevin-4-Oil |
| Carbofuran | 2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate | Furadan |
| Chlordecone | Decachloro-octahydro-1,3,4-metheno-2H-cyclobuta(cd)pentalene-2-one | Kepone |
| DDT | Dichloro diphenyl trichloroethane | None |
| Malathion | O,O-dimethyl-S-(1,2-dicarbethyoxyethyl)-phosphorodithioate | None |
| Methoxychlor | 2,2-bis(p-methoxyphenyl)-1,1,1-trichloroethane | None |

Table 19--Common and scientific names of fishes referred to in text and tables

| Common name | Scientific name |
|---|---|
| | FAMILY Catostomidae |
| Lake chubsucker | *Erimyzon sucetta* (Lacèpéde) |
| | FAMILY Centrarchidae |
| Bluegill | *Lepomis macrochirus* Rafinesque |
| Green sunfish | *Lepomis cyanellus* Rafinesque |
| Largemouth bass | *Micropterus salmoides* (Lacèpéde) |
| Pumpkinseed | *Lepomis gibbosus* (Linnaeus) |
| Smallmouth bass | *Micropterus dolomieui* Lacèpéde |
| | FAMILY Cottidae |
| Slimy sculpin | *Cottus cognatus* Richardson |
| | FAMILY Cyprinidae |
| Blacknose dace | *Rhinichthys atratulus* (Hermann) |
| Carp | *Cyprinus carpio* Linnaeus |
| Fathead minnow | *Pimephales promelas* Rafinesque |
| Goldfish | *Carassius auratus* (Linnaeus) |
| Lake emerald shiner | *Notropis atherinoides* Rafinesque |
| Redside shiner | *Richardsonius balteatus* (Richardson) |
| Stoneroller | *Campostoma anomalum* (Rafinesque) |
| | FAMILY Cyprinodontidae |
| Longnose killifish | *Fundulus similis* (Baird and Girard) |
| Sheepshead minnow | *Cyprinodon variegatus* Lacèpéde |
| | FAMILY Ictaluridae |
| Black bullhead | *Ictalurus melas* (Rafinesque) |
| Channel catfish | *Ictalurus punctatus* (Rafinesque) |
| | FAMILY Oryziidae |
| Medaka | *Oryzias latipes* (Temminck and Schlegel) |
| | FAMILY Percidae |
| Yellow perch | *Perca flavescens* (Mitchill) |
| Walleye | *Stizostedion vitreum* (Mitchill) |
| | FAMILY Poeciliidae |
| Guppy | *Poecilia reticulata* Peters |
| Mosquitofish, gambusia | *Gambusia affinis* (Baird and Girard) |
| | FAMILY Salmonidae |
| Atlantic salmon | *Salmo salar* Linnaeus |
| Brook trout | *Salvelinus fontinalis* (Mitchill) |
| Brown trout | *Salmo trutta* Linnaeus |
| Cherry salmon | *Oncorhynchus masou* (Brevort) |
| Chinook salmon | *Oncorhynchus tshawytscha* (Walbaum) |
| Chum salmon | *Oncorhynchus keta* (Walbaum) |
| Coho salmon | *Oncorhynchus kisutch* (Walbaum) |
| Cutthroat trout | *Salmo clarki* Richardson |
| Lahontan cutthroat trout | *Salmo clarki henshawi* Gill and Jordan |
| Lake trout | *Salvelinus namaycush* (Walbaum) |
| Pink salmon | *Oncorhynchus gorbuscha* (Walbaum) |
| Rainbow (steelhead) trout | *Salmo gairdneri* Richardson |
| Sockeye salmon | *Oncorhynchus nerka* (Walbaum) |
| Whitefish | *Prosopium* sp. |
| Whitefish | *Coregonus* sp. |
| | FAMILY Umbridae |
| Eastern mudminnow | *Umbra pygmaea* (DeKay) |

Table 20--Common and scientific names of invertebrates referred to in text and tables

| Common name | Scientific name |
|---|---|
|  | ORDER Amphipoda |
| Scuds, amphipods | *Gammarus fasciatus* Say |
|  | *Gammarus lacustris* Sars |
|  | *Gammarus pseudolimnaeus* Bousfield |
|  | ORDER Cladocera |
| Daphnids, water fleas | *Daphnia magna* Straus |
|  | *Daphnia pulex* Leydig |
|  | ORDER Decapoda |
| Crayfishes | *Orconectes nais* (Faxon) |
|  | *Procambarus clarki* (Girard) |
| Glass shrimp | *Palaemonetes kadiakensis* Rathbun |
|  | ORDER Diptera |
| Crane fly | *Tipula* sp. |
| Phantom midge | *Chaoborus* sp. |
| Midges | *Chironomus tenans* (Fabricius) |
|  | *Chironomus plumosus* (Linnaeus) |
|  | ORDER Ephemeroptera |
| Mayflies | *Hexagenia bilineata* (Say) |
|  | *Baetis* sp. |
|  | ORDER Gastropoda |
| Snails | *Helisoma campanulata* (Say) |
|  | *Stagnicola emarginata* (Say) |
|  | ORDER Isopoda |
| Sowbugs, isopods | *Asellus brevicaudus* Forbes |
|  | *Asellus hilgendorffii* |
|  | ORDER Megaloptera |
| Dobsonfly | *Nigronia* sp. |
|  | ORDER Odonata |
| Dragonfly | *Macromia* sp. |
| Damselfly | *Ischnura venticalis* (Say) |
|  | ORDER Ostracoda |
| Seed shrimp | *Cypridopsis vidua* (Müller) |
|  | ORDER Plecoptera |
| Stoneflies | *Pteronarcys californica* Newport |
|  | *Pteronarcys dorsata* Say |
|  | *Pteronarcella badia* (Hagen) |
|  | *Isoperla* sp. |
|  | *Skwala* sp. |
|  | ORDER Trichoptera |
| Caddisflies | *Hydropsyche* sp. |
|  | *Limnephilus* sp. |

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**Forest Service**

Pacific Northwest
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General Technical
Report
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February 1983

# Western Redcedar -- A Literature Review

Don Minore

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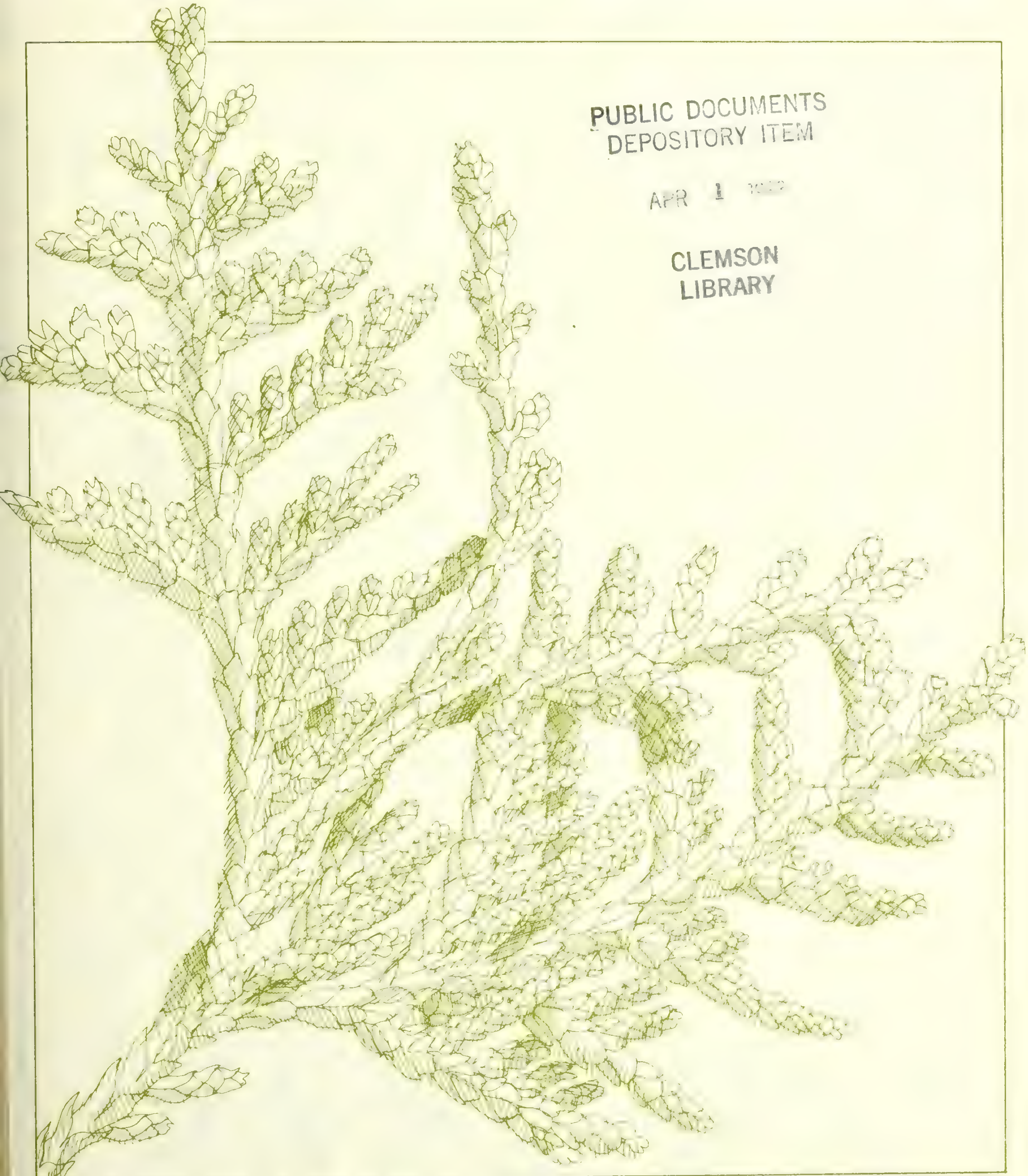

## Author

DON MINORE is plant ecologist,
Forestry Sciences Laboratory,
Pacific Northwest Forest and Range
Experiment Station, Corvallis,
Oregon.

## Abstract

Minore, Don.
1983. Western redcedar: A literature review. USDA For. Serv. Gen. Tech. Rep. PNW-150, 70 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

This report is a comprehensive compilation of information on western redcedar (*Thuja plicata* Donn) — its occurrence and abundance; associated plant species; morphology and anatomy; products; medical aspects; diseases; insect, bird, and mammal pests; genetics; horticulture; physiology; ecology; mensuration; and silviculture. Management recommendations and an extensive list of references are included.

Keywords: Western redcedar, *Thuja plicata,* silviculture, ecology, physiology, products.

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# Introduction

The western redcedar is the only *Thuja* species native to western North America.[1] (Northern white-cedar grows in eastern North America, and four other *Thuja* species occur in the Orient.) These members of the subfamily Thujoideae of the Cupressaceae are considered more highly evolved than *Libocedrus, Cupressus, Chamaecyparis,* or *Juniperus* species (see Moseley 1943).[2] Large western redcedars reach ages of 800 to 1,000 years, and some individuals in eastern Washington may be 2,000 years old (Sharpe 1974). General attributes of the species include a conical form with large and fluted base in mature trees, drooping branches, thin fibrous bark, and small scalelike leaves arranged in flat sprays (Sudworth 1908, Sharpe 1974).

Redcedar wood is valuable and used extensively. Use of redcedar products is far ahead of the management practices for replenishing the supply of high-quality timber from which most of those products are made. More efficient use of western redcedar and better management are needed; they can best be achieved by using available knowledge as a base for further advances. Considerable knowledge is available, but it is scattered in diverse publications under many subject headings and titles. This report summarizes most of the information in those publications for the scientists, administrators, and foresters who participate in western redcedar research, use, and silviculture.

# Occurrence and Abundance

## Range

Western redcedar grows along the Pacific coast from northern California to southeastern Alaska (fig. 1). It occurs sporadically at its southern limit in Humboldt County, California, where it is common only in the lower Mad River drainage and the wet region south of Ferndale (Griffin and Critchfield 1972). Elsewhere along the northern coast of California, western redcedar occurs only in isolated stands on boggy habitats.

North of the California-Oregon border, the natural range of western redcedar broadens to include portions of the Cascade Range. On the western slopes of the Cascades, redcedar grows from Crater Lake north (Boyd 1959, Little 1971). On the eastern slopes, it occurs north of approximately 44°30′N latitude (Franklin and Dyrness 1973). The redcedar populations of the Cascades and the coast meet occasionally in moist portions of the Willamette Valley, Oregon. Farther north, optimal growth and development are achieved near the latitudinal center of western redcedar's range — the Olympic Peninsula in Washington.

North of Vancouver Island, western redcedar is restricted to the Coast Ranges and coastal islands. The northern limits of its coastal range are the northern and western shores of Sumner Strait on Kupreanof and Kuiu Islands and the Petersburg vicinity on Mitkof Island (Harris and Farr 1974) at approximately 56°30′N latitude (see Andersen 1953). South of Petersburg, western redcedar occurs as an overstory dominant on former muskeg areas with shallow water tables (Stephens et al. 1970). It is common and important only farther south, however, near Ketchikan and Craig, in the intermediate types between bogs and upland forests (Neiland 1971).

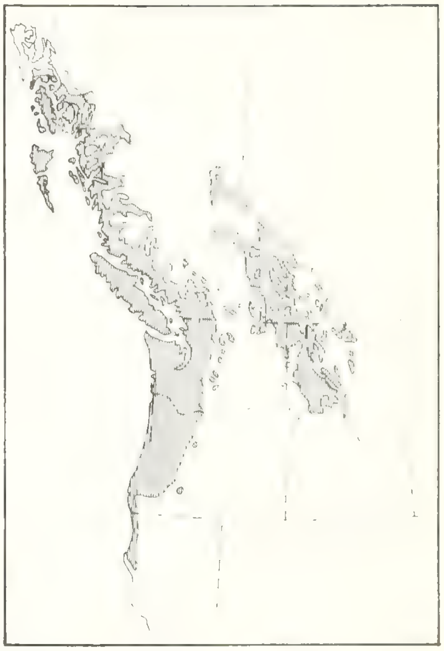

Figure 1.—The natural range of western redcedar (from Little 1971, Viereck and Little 1975).

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[1] Nomenclature for all northwestern plant species is according to Hitchcock and Cronquist 1973. Scientific names for trees mentioned by common name throughout the text are listed on page 50.

[2] Where information was derived from a publication, but not specifically stated therein, the author's name is prefaced by "see" (e.g., see Little 1971).

Near the southern border of British Columbia, a few scattered populations of western redcedar occur between the Coast Ranges and Selkirk Mountains, but the coastal range is essentially isolated from the interior range of the species. The northern limit of the interior range is on the western slope of the Continental Divide at 54°30′N latitude. The interior range extends south in British Columbia through the Selkirk Mountains into western Montana and northern Idaho (Boyd 1959). The southern limit of the interior range is in western Montana's Ravalli County at 45°50′N latitude (see Little 1971). With the possible exception of a few trees east of the Continental Divide near the upper end of St. Mary's Lake, the eastern limit is near Lake McDonald in Glacier National Park (Aller 1960).

Western redcedar grows from sea level to 915 m (3,000 ft) in southeastern Alaska (Viereck and Little 1972). In British Columbia, the elevation range is higher — from sea level to 1200 m (3,900 ft) (Anderson 1961). Interior redcedar is found from 320 m (1,050 ft) near Orofino, Idaho (personal communication, Charles A. Wellner, Forestry Sciences Laboratory, Moscow, Idaho), to 2100 m (7,000 ft) (Boyd 1959). The greatest range in elevation occurs in Oregon, however, where western redcedar occurs from sea level to 2300 m (7,500 ft) at the rim of Crater Lake (Sudworth 1908, Bowers 1956).

Coastal populations of western redcedar receive from less than 89 to more than 660 cm (less than 35 to more than 260 in) of annual rainfall. Interior populations receive about 71 cm (28 in) in the north, 81 to 124 cm (32 to 49 in) of annual precipitation farther south (Boyd 1959).

Where sufficient precipitation is present, temperature apparently limits the range of western redcedar. Schmidt (1958) measured an abrupt decrease in length of the frost-free period just above the upper elevational limits of western redcedar, western hemlock, and Douglas-fir on Vancouver Island. In southeastern Alaska, the northern limits of western redcedar are not correlated with rainfall or winter temperatures, but they are between the 11.1° and 11.7°C (52° and 53°F) mean summer temperature isotherms (Andersen 1953, 1955a). Average annual temperatures in inland portions of the redcedar range are lower than those along the coast (see Boyd 1959).

Western redcedar is often grown outside its natural range. In the United States, planted trees grow as far north as Juneau, Alaska (Harris and Farr 1974), and western redcedar is occasionally cultivated as an ornamental tree in the Middle and North Atlantic States (Sargent 1933). Redcedars have been cultivated as ornamentals in the Ukraine since 1870 (Unasylva 1950, Perepadya 1971). They are also used as ornamentals and hedge trees in southern Australia (Streets 1962). Western redcedar hedges are widely used in Britain (Hubbard 1950) and in Switzerland (see Keller 1974).

For years western redcedar has been used in practical forestry in England, Ireland, Scotland, and Wales (see Keatinge 1947, Zehetmayr 1954, Ovington and Madgwick 1957, O'Carroll 1967, Aldhous and Low 1974, Priest 1974, Carey and Barry 1975). It is also well established as a useful forestry species in West Germany (see Zimmerle and Linck 1951, Borchers 1952, Degen 1965, Hesmer and Gunther 1968, Volk 1968), East Germany (see Lembcke 1970), and Austria (see Rannert 1976). Indeed, the species is almost naturalized in West Germany (Volkert 1956). Experimental redcedar stands were established in Poland in 1890 (see Gecow 1952), and the species was recommended for practical forestry in Czechoslovakia (Holubčik 1968). It has been planted in Denmark and France since the 1860's (see Søegaard 1956b, Guinier 1951). Western redcedar plantations also have been established in Italy (Ministero dell'Agricoltura e delle Foreste, Collana Verde, Roma 1965). Redcedar has been grown in western Norway (Smitt 1950), but the northernmost stands on record are in Mustila, Finland, at 60°41′N latitude (Artsȳbashev 1939).

Western redcedar has been planted extensively in New Zealand (see Perham 1938, Hocking and Mayfield 1939, Ranger 1945, Streets 1962, and Weston 1971). It has also been successfully grown at higher elevations in Tasmania, but it grows relatively slowly in Kenya (Streets 1962). The species has shown little promise in the Union of South Africa (Streets 1962) or in central Honshu, Japan (see Kawada and Yamaji 1949).

## Volumes

Western redcedar is an important commercial species in much of its natural range. In North America, an estimated volume of 154 billion board feet (Scribner rule) exists in live western redcedar trees that are at least 25 percent sound (Bolsinger 1979). More than three-fourths of this volume (120 billion board feet by Bolsinger's estimate) occurs in British Columbia. Within British Columbia, 86 percent of the western redcedar volume is found in coastal areas (British Columbia Forest Service, Inventory Division 1967). The rest grows in the interior. When all trees larger than 25.4 cm (10 in) in diameter are considered, western redcedar accounts for about 11 percent of all the sound wood in mature, accessible commercial forests in British Columbia. In coastal areas, this proportion rises to 39 percent (Gardner 1963). When only the north coast forests of British Columbia are considered, western redcedar makes up 52 percent of the merchantable volume (McBride 1959). Although much of British Columbia's vast cedar resource is sawtimber, an estimated 121 million western redcedar poles also were included in 1961 (Anderson 1961).

In the United States, most western redcedars (13 billion board feet) grow in Washington. The greatest concentration is on the Olympic Peninsula in Clallam, Grays Harbor, and Jefferson Counties, where an additional 10 percent of the present live volume probably exists as dead cedars that are at least 25 percent sound (Bolsinger 1979). Bolsinger's compilations show that Idaho has 7.8 billion, Alaska 6.3 billion, Oregon 5 billion, Montana 1.4 billion, and California 76 million board feet of cedar volume. Three-fifths of it is in the National Forests, where most of the redcedar in Idaho, Montana, and Alaska occurs.

Bolsinger found that 66 percent of all western redcedar volume in the United States is in trees that are 53-cm (21-in) d.b.h. or larger, 44 percent is in trees larger than 74 cm (29 in). Average size is largest in Washington and smallest in Idaho. Most of the redcedar volume in Idaho occurred in 28- to 53-cm (11.0-to 20.9-in) d.b.h. trees in 1962 (see Wilson 1962).

# Associated Plant Species

## Trees

Pure western redcedar stands cover some small areas (Eyre 1980), but the species usually is associated with other tree species. These species are listed by locality in table 1.

Soil moisture conditions seem to be important in determining composition of local stands. Black cottonwood and bigleaf maple often grow with western redcedar in swamps (Sharpe 1974), as do both Pacific silver fir and western white pine in coastal swamps of the Olympic Peninsula (Franklin and Dyrness 1973). Dry-site associates include grand fir and lodgepole (shore) pine along the east coast of Vancouver Island (Packee 1976), Pacific madrone on the British Columbia mainland (see Krajina 1969), and western hemlock on the Queen Charlotte Islands (Day 1957).

Western hemlock and black cottonwood are associated with western redcedar throughout its natural range. Douglas-fir is present in all but the Alaska range. Pacific yew occurs only in the extreme south end of southeastern Alaska (Viereck and Little 1972), but it is often found as a redcedar associate elsewhere.

Western redcedar is a major species in two forest cover types recognized by the Society of American Foresters (Eyre 1980) — Western Redcedar and Western Redcedar-Western Hemlock. It occurs as a minor associated species in 10 types: Western Hemlock-Sitka Spruce, Coastal True Fir-Hemlock, Douglas-Fir-Western Hemlock, Pacific Douglas-Fir, Port-Orford-Cedar, Western Larch, Western White Pine, Engelmann Spruce-Subalpine Fir, Red Alder, and Redwood.

## Shrubs

*Rubus parviflorus* Nutt. is associated with western redcedar from Alaska to California and from coastal Washington and Oregon to Montana (table 2). Several other shrub associates occur in both interior and coastal environments (e.g., *Amelanchier alnifolia* Nutt., *Cornus stolonifera* Michx., *Menziesia ferruginea* Smith, *Oplopanax horridum* (Smith) Miq., *Pachistima myrsinites* (Pursh) Raf., *Rosa gymnocarpa* Nutt., and *Symphoricarpos albus* (L.) Blake), but some associated shrubs are more limited. *Sorbus, Lonicera,* and *Clematis* species are found with redcedar only in the interior; *Rubus spectabilis* Pursh and *Vaccinium parvifolium* Smith are associated only near the coast.

Shrub associates change less with latitude than they do with longitude, but two are noteworthy. *Rhododendron macrophyllum* G. Don is abundant in coastal California, Oregon, and Washington; it seems to be present in only two stands in southern British Columbia, however (see Packee 1976). In contrast, the northern limits of *Gaultheria shallon* Pursh are nearly the same as the northern limits of western redcedar in coastal Alaska (see Viereck and Little 1972, 1975).

Table 1 — Tree species associated with western redcedar in 7 portions of its natural range

| **Alaska**[1] | **Coastal British Columbia**[2] | **Interior British Columbia**[3] | **Montana**[4] |
|---|---|---|---|
| *Abies amabilis* | *Abies amabilis* | *Abies grandis* | *Abies grandis* |
| *Alnus rubra* | *Abies grandis* | *Abies lasiocarpa* | *Abies lasiocarpa* |
| *Chamaecyparis nootkatensis* | *Acer macrophyllum* | *Betula papyrifera* | *Betula papyrifera* |
| *Picea sitchensis* | *Alnus rubra* | *Larix occidentalis* | *Larix occidentalis* |
| *Pinus contorta* | *Arbutus menziesii* | *Picea engelmannii* | *Picea engelmannii* |
| *Populus trichocarpa* | *Betula papyrifera* | *Picea glauca* | *Picea glauca* |
| *Taxus brevifolia* | *Chamaecyparis nootkatensis* | *Pinus albicaulis* | *Pinus contorta* |
| *Tsuga heterophylla* | *Cornus nuttallii* | *Pinus contorta* | *Pinus monticola* |
| | *Picea sitchensis* | *Pinus monticola* | *Pinus ponderosa* |
| | *Pinus contorta* | *Populus tremuloides* | *Populus trichocarpa* |
| | *Pinus monticola* | *Populus trichocarpa* | *Pseudotsuga menziesii* |
| | *Populus tremuloides* | *Pseudotsuga menziesii* | *Taxus brevifolia* |
| | *Populus trichocarpa* | *Taxus brevifolia* | *Tsuga heterophylla* |
| | *Pseudotsuga menziesii* | *Tsuga heterophylla* | |
| | *Quercus garryana* | | |
| | *Taxus brevifolia* | | |
| | *Tsuga heterophylla* | | |
| | *Tsuga mertensiana* | | |

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[1] From Viereck and Little (1972).
[2] From Orloci (1961, 1965), Krajina (1969), Packee (1976).
[3] From McLean and Holland (1958), Bell (1965), Krajina (1969).
[4] From Pfister et al. (1977).
[5] From Daubenmire (1952), Daubenmire and Daubenmire (1968).
[6] From Franklin and Dyrness (1973), Dyrness et al. (1974).
[7] From Munz and Keck (1959), Axelrod (1977), Küchler (1977), Sawyer et al. (1977), Zinke (1977).

Table 1 — Continued

| Eastern Washington and northern Idaho[5] | Western Washington and Oregon[6] | California[7] |
|---|---|---|
| *Abies grandis* | *Abies amabilis* | *Abies grandis* |
| *Abies lasiocarpa* | *Abies grandis* | *Acer macrophyllum* |
| *Betula papyrifera* | *Abies procera* | *Alnus rubra* |
| *Larix occidentalis* | *Acer macrophyllum* | *Chamaecyparis lawsoniana* |
| *Picea engelmannii* | *Alnus rubra* | *Cornus nuttallii* |
| *Pinus contorta* | *Arbutus menziesii* | *Lithocarpus densiflorus* |
| *Pinus monticola* | *Calocedrus decurrens* | *Picea sitchensis* |
| *Pinus ponderosa* | *Castanopsis chrysophylla* | *Populus trichocarpa* |
| *Populus tremuloides* | *Chamaecyparis lawsoniana* | *Pseudotsuga menziesii* |
| *Populus trichocarpa* | *Chamaecyparis nootkatensis* | *Rhamnus purshiana* |
| *Pseudotsuga menziesii* | *Cornus nuttallii* | *Sequoia sempervirens* |
| *Taxus brevifolia* | *Lithocarpus densiflorus* | *Tsuga heterophylla* |
| *Tsuga heterophylla* | *Pinus contorta* | *Umbellularia californica* |
|  | *Pinus monticola* |  |
|  | *Picea engelmannii* |  |
|  | *Picea sitchensis* |  |
|  | *Populus tremuloides* |  |
|  | *Populus trichocarpa* |  |
|  | *Pseudotsuga menziesii* |  |
|  | *Taxus brevifolia* |  |
|  | *Tsuga heterophylla* |  |
|  | *Tsuga mertensiana* |  |

**Table 2 — Shrub species associated with western redcedar in 7 portions of its natural range**

| Alaska[1] | Coastal British Columbia[2] | Interior British Columbia[3] | Montana[4] |
|---|---|---|---|
| *Amelanchier alnifolia* var. *semiintegrifolia* | *Acer circinatum* | *Acer glabrum* | *Acer glabrum* |
| *Alnus sinuata* | *Alnus sinuata* | *Amelanchier alnifolia* | *Alnus incana* var. *occidentalis* |
| *Cladothamnus pyroliflorus* | *Amelanchier alnifolia* | *Arctostaphylos uva-ursi* | *Amelanchier alnifolia* |
| *Cornus stolonifera* | *Berberis nervosa* | *Ceanothus sanguineus* | *Arctostaphylos uva-ursi* |
| *Gaultheria shallon* | *Cladothamnus pyroliflorus* | *Cladothamnus pyroliflorus* | *Berberis aquifolium* |
| *Menziesia ferruginea* | *Cornus stolonifera* | *Cornus stolonifera* | *Berberis repens* |
| *Oplopanax horridum* | *Gaultheria shallon* | *Gaultheria ovatifolia* | *Ceanothus velutinus* |
| *Ribes bracteosum* | *Holodiscus discolor* | *Gaultheria shallon* | *Clematis columbiana* |
| *Ribes laxiflorum* | *Menziesia ferruginea* | *Juniperus communis* | *Cornus stolonifera* |
| *Rubus parviflorus* | *Myrica gale* | *Lonicera ciliosa* | *Holodiscus discolor* |
| *Rubus spectabilis* | *Oplopanax horridum* | *Lonicera involucrata* | *Lonicera utahensis* |
| *Salix barclayi* | *Physocarpus capitatus* | *Lonicera utahensis* | *Menziesia ferruginea* |
| *Salix scouleriana* | *Prunus emarginata* | *Menziesia ferruginea* | *Menziesia glabella* |
| *Salix sitchensis* | *Ribes bracteosum* | *Oplopanax horridum* | *Oplopanax horridum* |
| *Sambucus racemosa* ssp. *pubens* var. *arborescens* | *Rosa gymnocarpa* | *Pachystima myrsinites* | *Pachystima myrsinites* |
| *Vaccinium alaskaense* | *Rubus parviflorus* | *Prunus emarginata* | *Ribes lacustre* |
| *Vaccinium ovalifolium* | *Rubus spectabilis* | *Rhododendron albiflorum* | *Rosa gymnocarpa* |
| *Vaccinium parvifolium* | *Rubus ursinus* | *Ribes lacustre* | *Rubus parviflorus* |
| *Vaccinium uliginosum* | *Salix scouleriana* | *Ribes viscosissimum* | *Salix* sp. |
| *Viburnum edule* | *Sambucus ovatum* | *Rosa gymnocarpa* | *Shepherdia canadensis* |
| | *Sambucus racemosa* ssp. *pubens* | *Rubus nivalis* | *Sorbus sitchensis* |
| | *Spiraea douglasii* | *Rubus parviflorus* | *Sorbus scopulina* |
| | *Symphoricarpos albus* | *Salix scouleriana* | *Spiraea betulifolia* var. *lucida* |
| | *Symphoricarpos mollis* | *Sambucus racemosa* ssp. *pubens* | *Symphoricarpos albus* |
| | *Vaccinium alaskaense* | *Shepherdia canadensis* | *Symphoricarpos occidentalis* |
| | *Vaccinium myrtillus* | *Sorbus sitchensis* | *Vaccinium globulare* |
| | *Vaccinium ovalifolium* | *Spiraea betulifolia* var. *lucida* | *Vaccinium membranaceum* |
| | *Vaccinium ovatum* | *Spiraea douglasii* | *Vaccinium myrtillus* |
| | *Vaccinium parvifolium* | *Vaccinium membranaceum* | *Vaccinium scoparium* |
| | *Vaccinium uliginosum* | *Vaccinium myrtillus* | |
| | *Viburnum opulus* var. *americanum* | *Vaccinium ovalifolium* | |
| | | *Viburnum edule* | |
| | | *Viburnum opulus* var. *americanum* | |

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[1] From Viereck and Little (1972); personal communication from Paul Alaback, Department of Forest Science, Oregon State University, Corvallis, 1980.

[2] From Orloci (1961, 1965), Krajina (1969), Packee (1976).

[3] From McLean and Holland (1958), Bell (1965), Krajina (1969).

[4] From Aller (1960), Pfister et al. (1977).

[5] From Daubenmire (1952), Daubenmire and Daubenmire (1968).

[6] From Fonda and Bliss (1969), Franklin and Dyrness (1973), Dyrness et al. (1974).

[7] From Munz and Keck (1959), Axelrod (1977), Küchler (1977), Sawyer et al. (1977), Zinke (1977).

Table 2 — Continued

| Eastern Washington and northern Idaho[5] | Western Washington and Oregon[6] | California[7] |
|---|---|---|
| *Acer glabrum* | *Acer circinatum* | *Acer circinatum* |
| *Alnus sinuata* | *Amelanchier alnifolia* | *Berberis nervosa* |
| *Amelanchier alnifolia* | *Berberis nervosa* | *Corylus cornuta* |
| *Arctostaphylos uva-ursi* | *Corylus cornuta* | *Gaultheria shallon* |
| *Clematis columbiana* | *Gaultheria shallon* | *Holodiscus discolor* |
| *Cornus stolonifera* | *Menziesia ferruginea* | *Myrica californica* |
| *Corylus cornuta* | *Oplopanax horridum* | *Rhododendron macrophyllum* |
| *Lonicera utahensis* | *Pachystima myrsinites* | *Rhododendron occidentale* |
| *Menziesia ferruginea* | *Rhododendron macrophyllum* | *Ribes bracteosum* |
| *Oplopanax horridum* | *Ribes lacustre* | *Rosa gymnocarpa* |
| *Pachystima myrsinites* | *Rosa gymnocarpa* | *Rubus parviflorus* |
| *Ribes lacustre* | *Rosa nutkana* | *Rubus spectabilis* |
| *Ribes viscosissimum* | *Rubus nivalis* | *Rubus ursinus* |
| *Rosa gymnocarpa* | *Rubus parviflorus* | *Vaccinium ovatum* |
| *Rubus idaeus* | *Rubus ursinus* | *Vaccinium parvifolium* |
| *Rubus parviflorus* | *Rubus spectabilis* | |
| *Sambucus racemosa* ssp. *pubens* | *Salix hookeriana* | |
| *Sorbus scopulina* | *Sorbus sitchensis* | |
| *Spiraea betulifolia* var. *lucida* | *Spiraea douglasii* | |
| *Symphoricarpos albus* | *Symphoricarpos albus* | |
| *Vaccinium membranaceum* | *Symphoricarpos mollis* | |
| *Vaccinium ovalifolium* | *Vaccinium alaskaense* | |
| | *Vaccinium membranaceum* | |
| | *Vaccinium ovalifolium* | |
| | *Vaccinium ovatum* | |
| | *Vaccinium parvifolium* | |

## Herbs

Some of the herbs associated with western redcedar are listed in table 3. Fourteen associates are common in both coastal and interior environments: *Athyrium filix-femina* (L.) Roth., *Chimaphila umbellata* (L.) Bart., *Clintonia uniflora* (Schult.) Kunth., *Cornus canadensis* L., *Dryopteris austriaca* (Jacq.) Woynar, *Galium trifidum* L., *Gymnocarpium dryopteris* (L.) Newm., *Linnaea borealis* L., *Polystichum munitum* (Kaulf.) Presl, *Pteridium aquilinum* (L.) Kuhn., *Rubus pedatus* J. E. Smith, *Streptopus amplexifolius* (L.) DC., *Tiarella trifoliata* L., and *Viola glabella* Nutt. Two other common associates (*Carex obnupta* Bailey and *Oenanthe sarmentosa* Presl) are limited to moist habitats west of the Cascades. *Aralia nudicaulis* L. and *Coptis occidentalis* (Nutt.) T. & G. occur with redcedar only in the interior.

## Major Communities

Krajina (1969) described 23 British Columbia "Biogeocoenoses" that contain western redcedar as a component. The communities represented are listed in table 4. The communities of Orloci (1961, 1965) and Brooke (1965) on the southwestern British Columbia mainland also are listed in table 4. *Thuja/Polystichum* occurs on moist, concave lower slopes. *Thuja/Lysichitum* also occurs on lower slopes, but only in swampy situations and on wet outwash terraces where the ground water table is near the surface and flowing. *Thuja/Coptis* is found in swampy depressions where the ground water is stagnant, and *Thuja/Oplopanax* occurs in swampy ravines where the ground water overflows intermittently. *Thuja-Abies amabilis/Oplopanax* occurs along stream margins at 1067- to 1219-m (3,500- to 4,000-ft) elevations where nonstagnant ground water is near the surface. It is of limited occurrence.

Three of Bell's (1965) major plant communities for the Selkirk and Monashee Mountains of southeastern British Columbia include western redcedar. The *Aralia/Gymnocarpium* community occurs on slopes and alluvial flats where subsurface water is available. *Oplopanax* communities are found on steep lower slopes with permanent seepage at or near the surface and on alluvial flats with high water tables. The *Lysichitum* community is present where soil is saturated by slowly moving ground water for much of the growing season. A similar *Thuja/Lysichitum* community occurs in the coastal environment of Vancouver Island's Nanaimo River Valley (see McMinn 1960).

Daubenmire and Daubenmire (1968) recognized three western redcedar communities in northern Idaho. *Thuja plicata/Pachistima myrsinites* is an upland community where *Athyrium* is absent or short and *Tsuga* is absent. Hanley's (1976) biomass estimates indicate that this community is very productive. *Thuja plicata/Oplopanax horridum* and *Thuja plicata/Athyrium filix-femina* occur on bottomlands where *Athyrium* is usually abundant and tall. *Oplopanax* is present in the former, absent in the latter.

Three additional Idaho redcedar communities occur on the North Fork of the Clearwater River: *Thuja plicata/Adiantum pedatum* is common, *Thuja plicata/Dryopteris* spp. is uncommon, and *Thuja plicata/Lysichitum americanum* is rare (Steele 1971). A fourth (*Thuja plicata/Asarum caudatum)* is common in Nezperce County, Idaho (Steele et al. 1976).

Pfister et al. (1977) described two western redcedar communities in Montana that are essentially similar to the Daubenmires' communities in Idaho — *Thuja plicata/Oplopanax horridum* and *Thuja plicata/Clintonia uniflora.* The latter corresponds to the Daubenmires' *Thuja plicata/Pachistima myrsinites* community, but it includes a *Menziesia ferruginea* phase not present in Idaho. Two unnamed communities described by McLean and Holland (1958) in the upper Columbia River Valley also correspond to the Daubenmires' *Thuja/Oplopanax* and *Thuja/Pachistima* communities.

Bailey (1966) described a *Thuja plicata/Adiantum pedatum-Athyrium filix-femina* community in the southern Oregon Coast Ranges of eastern Coos and western Douglas Counties. *Polystichum munitum* and *Oxalis oregana* dominated the herb layer, but Bailey used the high constancy, low cover *Adiantum* and *Athyrium* as indicator species for this community. It occurred at low elevations on steep lower and middle slopes.

Franklin and Dyrness (1973) summarized the community information available from Oregon and Washington in 1973. They included two San Juan Island communities described in a 1973 report.[3] *Thuja plicata-Abies grandis/Pachistima myrsinites* occurs on moderately moist, north-facing slopes and level areas in the interior of Sucia Island. The moistest sites in the interior valley of Sucia Island support *Thuja plicata-Abies grandis/Polystichum munitum.* A report[4] is cited by Franklin and Dyrness (1973) in referring to a *Thuja plicata-Acer circinatum*/herb community found in moderately moist valleys of Washington's North Cascades National Park. Finally, Franklin and Dyrness (1973) described and photographed the *Thuja plicata-Tsuga heterophylla/Oplopanax horridum/Athyrium filix-femina* community. It occurs on very wet slopes and stream terraces in western Washington and is characterized by an extremely lush understory.

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[3] Unpublished report, "Preliminary report on the vegetation of the San Juan Islands, Washington," by R.W. Fonda and J.A. Bernardi. 1973. On file, Forestry Sciences Laboratory, Corvallis, Oregon.

[4] Unpublished report, "Phytosociological reconnaissance of western redcedar stands in four valleys of the North Cascades Park complex," by Joseph W. Miller and Margaret M. Miller. 1970. On file, Forestry Sciences Laboratory, Corvallis, Oregon.

**Table 3 — Herb species associated with western redcedar in 7 portions of its natural range**

| Alaska[1] | Coastal British Columbia[2] | Interior British Columbia[3] | Montana[4] |
|---|---|---|---|
| *Athyrium filix-femina* | *Achlys triphylla* | *Adenocaulon bicolor* | *Actaea rubra* |
| *Blechnum spicant* | *Adiantum pedatum* | *Adiantum pedatum* | *Adenocaulon bicolor* |
| *Clintonia uniflora* | *Anemone occidentalis* | *Angelica arguta* | *Aralia nudicaulis* |
| *Coptis asplenifolia* | *Athyrium filix-femina* | *Aralia nudicaulis* | *Athyrium filix-femina* |
| *Cornus canadensis* | *Blechnum spicant* | *Athyrium filix-femina* | *Carex disperma* |
| *Dryopteris austriaca* | *Cardamine breweri* | *Campanula rotundifolia* | *Chimaphila umbellata* |
| *Epilobium alpinum* var. *nutans* | *Carex deweyana* | *Carex disperma* | *Circaea alpina* |
| *Gymnocarpium dryopteris* | *Carex hendersonii* | *Carex laeviculmis* | *Clintonia uniflora* |
| *Hypopitys monotropa* | *Carex obnupta* | *Carex stipata* | *Coptis occidentalis* |
| *Listera cordata* | *Carex pauciflora* | *Chimaphila umbellata* | *Cornus canadensis* |
| *Lysichitum americanum* | *Chimaphila menziesii* | *Circaea alpina* | *Disporum hookeri* |
| *Maianthemum dilatatum* | *Chimaphila umbellata* | *Clintonia uniflora* | *Disporum trachycarpum* |
| *Polypodium glycyrrhiza* | *Circaea alpina* | *Corallorhiza maculata* | *Galium boreale* |
| *Pteridium aquilinum* | *Clintonia uniflora* | *Corallorhiza mertensiana* | *Galium trifidum* |
| *Pyrola uniflora* | *Coptis asplenifolia* | *Cornus canadensis* | *Goodyera oblongifolia* |
| *Rubus pedatus* | *Coptis trifolia* | *Corydalis sempervirens* | *Gymnocarpium dryopteris* |
| *Streptopus amplexifolius* | *Corallorhiza maculata* | *Dryopteris austriaca* | *Linnaea borealis* |
| *Streptopus roseus* var. *curvipes* | *Cornus canadensis* | *Equisetum palustre* | *Listera borealis* |
| *Streptopus streptopoides* | *Disporum hookeri* | *Equisetum scirpoides* | *Listera convallarioides* |
| *Thelypteris phegopteris* | *Drosera rotundifolia* | *Equisetum sylvaticum* | *Lycopodium annotinum* |
| *Tiarella trifoliata* | *Dryopteris austriaca* | *Fragaria virginiana* var. *glauca* | *Lycopodium complanatum* |
| | *Epilobium angustifolium* | *Galium boreale* | *Polystichum munitum* |
| | *Equisetum telmateia* | *Galium trifidum* | *Pteridium aquilinum* |
| | *Eriophorum chamissonis* | *Geum macrophyllum* | *Pyrola asarifolia* |
| | *Galium trifidum* | *Glycera elata* | *Pyrola chlorantha* |
| | *Glycera elata* | *Goodyera oblongifolia* | *Pyrola secunda* |
| | *Glycera striata* | *Gymnocarpium dryopteris* | *Smilacina stellata* |
| | *Goodyera oblongifolia* | *Heuchera cylindrica* | *Smilacina racemosa* |
| | *Gymnocarpium dryopteris* | *Linnaea borealis* | *Streptopus amplexifolius* |
| | *Linnaea borealis* | *Listera caurina* | *Tiarella trifoliata* var. *trifoliata* |
| | *Listera caurina* | *Listera convallarioides* | *Tiarella trifoliata* var. *unifoliata* |
| | *Listera cordata* | *Lycopodium complanatum* | *Trillium ovatum* |
| | *Lycopodium clavatum* | *Lysichitum americanum* | *Valeriana sitchensis* |
| | *Lycopodium complanatum* | *Melampyrum lineare* | *Veratrum viride* |
| | *Lycopodium selago* | *Mitella breweri* | *Viola canadensis* |
| | *Lysichitum americanum* | *Mitella pentandra* | *Viola glabella* |
| | *Maianthemum dilatatum* | *Polypodium glycyrrhiza* | *Viola orbiculata* |
| | *Mimulus moschatus* | *Polystichum andersonii* | *Xerophyllum tenax* |
| | *Mitella ovalis* | *Polystichum lonchitis* | |
| | *Monotropa uniflora* | *Pteridium aquilinum* | |
| | *Montia sibirica* | *Pyrola asarifolia* | |
| | *Oenanthe sarmentosa* | *Pyrola chlorantha* | |
| | *Polysticum munitum* | *Pyrola picta* | |
| | *Pteridium aquilinum* | *Pyrola secunda* | |
| | *Rubus pedatus* | *Rubus pedatus* | |
| | *Scirpus microcarpus* | *Scirpus microcarpus* | |
| | *Smilacina stellata* | *Smilacina stellata* | |
| | *Stachys mexicana* | *Smilacina racemosa* | |
| | *Stellaria crispa* | *Streptopus amplexifolius* | |
| | *Streptopus amplexifolius* | *Streptopus roseus* var. *curvipes* | |
| | *Streptopus roseus* var. *curvipes* | *Streptopus streptopoides* | |
| | *Streptopus streptopoides* | *Thalictrum occidentale* | |
| | *Tiarella trifoliata* var. *laciniata* | *Tiarella trifoliata* var. *laciniata* | |
| | *Tiarella trifoliata* var. *trifoliata* | *Tiarella trifoliata* var. *trifoliata* | |
| | *Tiarella trifoliata* var. *unifoliata* | *Tiarella trifoliata* var. *unifoliata* | |
| | *Tofieldia glutinosa* | *Trisetum cernuum* | |
| | *Trillium ovatum* | *Veratrum viride* | |
| | *Trisetum cernuum* | *Viola adunca* | |
| | *Veratrum viride* | *Viola glabella* | |
| | *Viola glabella* | *Viola palustris* | |
| | *Viola orbiculata* | *Woodsia scopulina* | |

Table 3 — Continued

| Eastern Washington and northern Idaho[5] | Western Washington and Oregon[6] | California[7] |
|---|---|---|
| *Actaea rubra* | *Achlys triphylla* | *Carex obnupta* |
| *Adenocaulon bicolor* | *Adenocaulon bicolor* | *Epilobium angustifolium* |
| *Adiantum pedatum* | *Adiantum pedatum* | *Erechtites arguta* |
| *Anemone piperi* | *Anemone deltoidea* | *Erechtites minima* |
| *Aralia nudicaulis* | *Asarum caudatum* | *Oxalis oregana* |
| *Asarum caudatum* | *Athyrium filix-femina* | *Polystichum munitum* |
| *Athyrium filix-femina* | *Blechnum spicant* | *Pteridium aquilinum* |
| *Carex laeviculmis* | *Campanula scouleri* | *Viola sempervirens* |
| *Chimaphila menziesii* | *Carex obnupta* | |
| *Chimaphila umbellata* | *Chimaphila menziesii* | |
| *Circaea alpina* | *Chimaphila umbellata* | |
| *Clintonia uniflora* | *Circaea alpina* | |
| *Coptis occidentalis* | *Clintonia uniflora* | |
| *Corallorhiza maculata* | *Coptis laciniata* | |
| *Corallorhiza mertensiana* | *Corallorhiza mertensiana* | |
| *Corallorhiza trifida* | *Cornus canadensis* | |
| *Cornus canadensis* | *Disporum hookeri* | |
| *Disporum hookeri* | *Disporum smithii* | |
| *Dryopteris austriaca* | *Dryopteris austriaca* | |
| *Dryopteris filix-mas* | *Galium oreganum* | |
| *Epilobium angustifolium* | *Galium trifidum* | |
| *Fragaria vesca* var. *bracteata* | *Goodyera oblongifolia* | |
| *Galium trifidum* | *Gymnocarpium dryopteris* | |
| *Goodyera oblongifolia* | *Linnaea borealis* | |
| *Gymnocarpium dryopteris* | *Listera caurina* | |
| *Hypopitys monotropa* | *Lycopodium clavatum* | |
| *Linnaea borealis* | *Lysichitum americanum* | |
| *Listera caurina* | *Maianthemum dilatatum* | |
| *Listera convallarioides* | *Mitella* sp. | |
| *Lysichitum americanum* | *Montia sibirica* | |
| *Mertensia paniculata* | *Oenanthe sarmentosa* | |
| *Mitella pentandra* | *Osmorhiza purpurea* | |
| *Mitella stauropetala* | *Oxalis oregana* | |
| *Montia sibirica* | *Polystichum munitum* | |
| *Polystichum munitum* | *Pteridium aquilinum* | |
| *Pteridium aquilinum* | *Pyrola asarifolia* | |
| *Pterospora andromedea* | *Pyrola picta* | |
| *Pyrola asarifolia* | *Pyrola secunda* | |
| *Pyrola chlorantha* | *Rubus lasiococcus* | |
| *Pyrola picta* | *Rubus pedatus* | |
| *Pyrola secunda* | *Smilacina stellata* | |
| *Pyrola uniflora* | *Stachys mexicana* | |
| *Rubus pedatus* | *Streptopus amplexifolius* | |
| *Smilacina racemosa* | *Streptopus roseus* var. *curvipes* | |
| *Smilacina stellata* | *Synthyris reniformis* | |
| *Stellaria crispa* | *Tiarella trifoliata* var. *trifoliata* | |
| *Streptopus amplexifolius* | *Tiarella trifoliata* var. *unifoliata* | |
| *Tiarella trifoliata* var. *trifoliata* | *Tolmiea menziesii* | |
| *Tiarella trifoliata* var. *unifoliata* | *Trientalis latifolia* | |
| *Trillium ovatum* | *Trillium ovatum* | |
| *Trisetum cernuum* | *Vancouveria hexandra* | |
| *Veratrum viride* | *Viola glabella* | |
| *Viola glabella* | *Viola sempervirens* | |
| *Viola orbiculata* | *Whipplea modesta* | |
| *Xerophyllum tenax* | *Xerophyllum tenax* | |

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[1] Personal communication, Paul Alaback, Department of Forest Science, Oregon State University, Corvallis, 1980.
[2] From Orloci (1961, 1965), Krajina (1969), Packee (1976).
[3] From McLean and Holland (1958), Bell (1965), Krajina (1969).
[4] From Aller (1960), Pfister et al. (1977).
[5] From Daubenmire (1952), Daubenmire and Daubenmire (1968), Steele (1971).
[6] From Fonda and Bliss (1969), Franklin and Dyrness (1973), Dyrness et al. (1974).
[7] From Munz and Keck (1959), Axelrod (1977), Küchler (1977), Sawyer et al. (1977), Zinke (1977).

**Table 4 — Major western redcedar communities in 5 portions of its native range[1]**

| Coastal British Columbia[2] | Interior British Columbia[3] | Montana[4] | Eastern Washington and northern Idaho[5] | Western Washington and Oregon[6] |
|---|---|---|---|---|
| (1) Thpl-Abam/Opho/Gydr-Atfi | (1) Thpl/Lyam | (1) Thpl/Clun | (1) Thpl/Atfi | (1) Thpl/Adpe-Atfi |
| (2) Thpl-Abam-Psme/Vaov | (2) Thpl/Opho/Tiun | (2) Thpl/Opho | (2) Thpl/Opho | (2) Thpl-Abgr/Pamy |
| (3) Thpl-Abam-Psme/Vaov-Vaal/Stro-Pomu-Blsp | (3) Thpl-Potr-Pien/Cost/Pyas-Smst | | (3) Thpl/Pamy | (3) Thpl-Abgr/Pomu |
| (4) Thpl-Abgr-Psme/Syal/Titr-Pomu | (4) Thpl-Psme/Loin/Arnu-Gydr-Clun-Tiun | | (4) Thpl/Adpe | (4) Thpl-Acci/herbs |
| (5) Thpl-Abgr-Psme/Titr-Pomu | (5) Thpl-Tshe-Psme-Pimo/Pamy/Coca | | (5) Thpl/Dr | (5) Thpl-Tshe/Opho/Atfi |
| (6) Thpl-Abgr/Syal/Adpe | (6) Psme-Thpl-Pimo/Vaov-Pamy/Coca-Tiun | | (6) Thpl/Lyam | |
| (7) Thpl-Chno-Abam-Psme/Vaov-Bene | (7) Tshe-Thpl-Psme/Lout/Arnu-Gydr-Coca-Clun-Tiun | | (7) Thpl/Asca | |
| (8) Thpl-Pisi-Abam/Opho-Ribr-Rusp/Pomu | (8) Arnu-Gydr | | | |
| (9) Thpl-Pisi-Abam-Psme/Pomu | (9) Opho | | | |
| (10) Thpl-Pisi-Alru/Lyam/Caob | (10) Lyam | | | |
| (11) Thpl-Pisi-Pico/Spdo | | | | |
| (12) Thpl-Psme/Bene | | | | |
| (13) Thpl-Psme/Pomu-Actr | | | | |
| (14) Thpl-Psme-Quga/Syal/Pomu | | | | |
| (15) Psme-Thpl/Gash-Symo-Bene | | | | |
| (16) Tshe-Thpl-Abam-Psme/Vaal/Blsp | | | | |
| (17) Thpl/Pomu | | | | |
| (18) Thpl/Vaal/Lyam | | | | |
| (19) Thpl/Coas-Cotr-Lyam | | | | |
| (20) Thpl/Opho/Adpe | | | | |
| (21) Thpl-Abam/Opho | | | | |
| (22) Thpl/Lyam | | | | |

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[1] Only the first two letters of each genus and species are listed (e.g. *Thuja plicata* = Thpl).

[2] Numbers 1-16 are from Krajina (1969); 17-20 are from Orloci (1965); 21 is from Brooke (1965); 22 is from McMinn (1960).

[3] Numbers 1-7 are from Krajina (1969); 8-10 are from Bell (1965).

[4] From Pfister (1977).

[5] Numbers 1-3 are from Daubenmire and Daubenmire (1968); 4-6 are from Steele (1971); 7 is from Steele et al. (1976).

[6] Number 1 is from Bailey (1966); 2-5 are from Franklin and Dyrness (1973).

# Morphology, Anatomy, and Composition

## Form

Western redcedar trees typically attain heights of 60+ m (197+ ft) and diameters of 150-300 cm (59-118 in) (Franklin and Dyrness 1973), but more massive individuals are not uncommon. Trees measuring 4.9 to 6.1 m (16 to 20 ft) in diameter and up to 76 m (250 ft) tall have been found (West Coast Lumber Trade Extension Bureau 1927). The largest western redcedar known to be alive in 1977 grew on the Olympic Peninsula. It was 592 cm (233 in) in diameter at breast height and 54 m (178 ft) tall (Pardo 1978). The largest redcedar east of the Cascades may be a tree 550 cm (216 in) in diameter and 54 m (177 ft) high, measured recently near Elk River, Idaho (personal communication, Charles A. Wellner, Forestry Sciences Laboratory, Moscow, Idaho).

Large western redcedar trees are not uncommon east of the Cascades. A preliminary survey of western redcedar in the northern Rocky Mountains[5] showed 33 groves containing redcedars larger than 152 cm (5 ft) d.b.h. Six contained trees larger than 335 cm (11 ft) d.b.h. The groves are quite evenly distributed among habitat types, but the *Thuja plicata/Athyrium filix-femina* type seems to be most typical. Although many groves occur on sideslopes, most of the very large western redcedars were found in stream bottoms or upper basins.

Wherever redcedars grow, the boles of old trees tend to be swollen or flared at the base (fig. 2). They are often conspicuously fluted, with frequent bark seams (Sudworth 1908, McBride 1959), but the fluting seems to be more common in open-grown trees than in dense stands (Nystrom 1980). Two or more leaders are frequent (Bowers 1956, Day 1957), and many old trees have hollow bases (McBride 1959, Daubenmire and Daubenmire 1968). Mature western redcedar trees tend to be larger in diameter but shorter than mature western hemlock, Sitka spruce, or Douglas-fir (Day 1957, Smith et al. 1961a).

Mature western redcedars taper more than Douglas-firs and western hemlocks. The majority of this taper is in the first 16 feet, and most occurs in the first 4 feet above ground (Nystrom 1980). Small western redcedar trees seem to taper less than large trees, which become nearly conical in southeastern Alaska (Andersen 1955a). Alaska redcedars growing in association with western hemlocks have much better form than those growing in pure stands (Andersen 1955b); this may be caused by the greater stand densities associated with hemlock-redcedar mixtures. Or it may be the result of mixed stands occurring on better sites than pure stands (see Gregory 1957).

## Crown, Branches, and Foliage

Most western redcedar trees growing on moderately dry sites in western Oregon have rather open crowns (see Gratkowski 1956). Crown density seems to vary with age, however. Young redcedars on the Queen Charlotte Islands have dense crowns that become thinner with age until the upper portions die, leaving numerous spike tops (Day 1957). This thinning with age is accompanied by changes in the percentages of stem wood, stem bark, branches, and foliage in western redcedar trees. Branches accounted for about 14 percent of the aboveground weight of the 5- to 15-cm (2- to 6-in) d.b.h. redcedars measured by Smith and DeBell (1973), but only 11 percent of the weight of those that were 30 to 41 cm (12 to 16 in) d.b.h. Individual trees vary greatly, however; the two redcedars measured by Grier and Logan (1977) were 23 and 41 cm (9 and 16 in) d.b.h. and had about 18 percent of their weight in living branches.

The branches of young western redcedars curve upward. On older trees they swing downward near the bole, then sweep up again at the ends (Bowers 1956). Except where densely crowded, most of these branches are retained until the trees are 46- to 51-cm (18- to 20-in) d.b.h. and 15 to 24 m (50 to 80 ft) tall (Sudworth 1908). Tiny branchlets are formed when the terminal shoot on each branch produces a lateral apex at every eighth leaf pair (see Malcolm and Caldwell 1971). These branchlets (really frondlike aggregations of leaves) die and fall off every 2 to 5 years (see Sudworth 1908, Bowers 1956).

The leaves of a mature western redcedar are small and scalelike — much smaller than the two cotyledons of a germinating seedling or the juvenile leaves produced in whorls of four soon thereafter (see Franklin 1961). They are darker green on top and lighter underneath than other cedarlike trees of the Pacific Northwest (Bowers 1956), with white markings on the lower surfaces (Dallimore and Jackson 1967).

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[5] Paper, "Western redcedar groves in the northern Rocky Mountains," by Frederic D. Johnson. 1980. Presented at the 53d annual meeting, Northwest Scientific Association, in Moscow, Idaho. Abstract on file, Forestry Sciences Laboratory, Corvallis, Oregon.

Western redcedar leaves are numerous, and foliage comprises a higher fraction of the live-crown weight in redcedar than it does in Douglas-fir (Brown 1978). Foliage accounts for 10 percent of the aboveground weight of 5- to 15-cm (2- to 6-in) d.b.h. redcedars and 6 percent of the weight of 30- to 41 cm (12- to 16-in) d.b.h. western redcedars (Smith and DeBell 1973). A 0.6- to 0.9-m (2- to 3-ft) diameter redcedar may have 227 to 1361 kg (500 to 3,000 lb) of green foliage (Cochrane 1951), but Grier and Logan (1977) measured an average of only 15.4 kg (33.9 lb) of ovendry foliage on 0.2- and 0.4-m (0.8- and 1.3-ft) diameter trees.

Redcedar foliage seems well suited to the support of epiphytes. Four species of mosses, 1 hepatic, and 16 lichen species occur on western redcedar leaves in western British Columbia (Vitt et al. 1973). Daubenmire (1943) also found lichens on the leaves of western redcedar in northern Idaho. He described three unique attributes that may be responsible for the superiority of redcedar foliage as an epiphyte habitat: overlapping of the scalelike leaves, the surface roughness created by peglike papillae projecting from epidermal cells, and a superficial film of scurfy material. Vitt et al. (1973) proposed a fourth attribute — lack of certain inhibitory volatile compounds that are found in the foliage of other western conifers.

Epiphyte-inhibiting compounds may not be present, but western redcedar foliage contains several other substances. The volatile foliage oil is chiefly L-thujone and d-isothujone (Von Rudloff 1962), but pinene, d-sabinene, and fenchone are also present (Cochrane 1951, Von Rudloff 1962, Banthorpe et al. 1973). Oil from young branchlets contains larger amounts of pinene and sabinene than that from older ones (Von Rudloff 1962). In addition to the above monoterpenes, diterpene hydrocarbons (Aplin and Cambie 1964), biflavonyl pigments (Rahman et al. 1972), and dilignol rhamnosides (Manners and Swan 1971, 1977) have also been found in western redcedar leaves. Some of these compounds inhibit bacterial growth (Michel 1976). Those present in the steam volatiles obtained from redcedar foliage are highly toxic to coho salmon fry (Peters 1974, Peters et al. 1976).

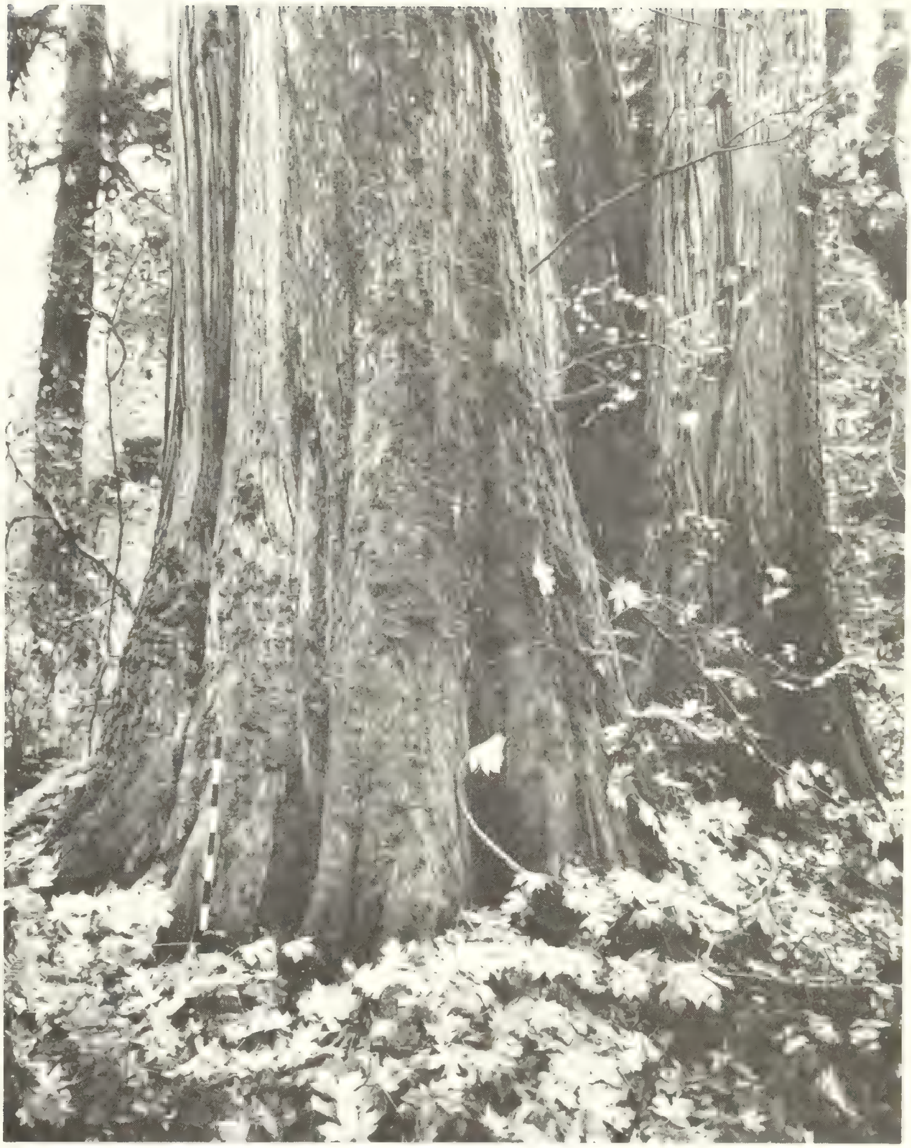

Figure 2.—Old-growth western redcedars. Note the fluted, flared lower boles. The striped stick is 1 m long.

The dry, powdered western redcedar foliage analyzed by Chow (1977a) had a pH of 5.3 — equal to the pH of red alder foliage, but much higher than the pH values measured for Douglas-fir (3.8), western hemlock (4.0), lodgepole pine (4.3), or white spruce (4.3) foliage. This high pH value was accompanied by a high calcium content. Ovington (1953) analyzed fresh leaves and also found higher pH values in redcedar than in Douglas-fir or western hemlock when all three species were measured on the same British site. He recorded great variation among sites, however, and concluded that leaf pH was related to acidity of the underlying soil.

When litter fall was analyzed near the Pacific coast, the calcium concentration in western redcedar foliage was over 2 percent — twice that of bigleaf maple foliage and 30 times that of lodgepole pine foliage (Tarrant et al. 1951). Calcium content was also high in freshly fallen western redcedar foliage in the northern Rocky Mountains (Daubenmire 1953). Nitrogen and phosphorus concentrations were relatively low for western redcedar foliage in both regions. Potassium concentrations were moderately high along the coast, moderately low in the northern Rocky Mountains. Packee's (1975) literature review showed that crude protein content of western redcedar foliage on Vancouver Island varies seasonally but is lower than that of Douglas-fir foliage. Western redcedar foliage apparently contains more fat than Douglas-fir foliage in July and December, less in March.

Redcedar does not form buds containing preformed shoots (Owens and Pharis 1971), and no clearly visible buds or rapidly elongating succulent shoots are present (Aldhous and Low 1974). Instead, the shoot apex is covered by numerous leaf primordia at various stages of development. Owens and Pharis found that branches are two ranked, occurring every two to four nodes. Only one branch occurs at a node, and secondary branches are more abundant on the side closest to the apex of the main branch.

## Strobili and Seeds

Male and female strobili are borne on different branches of the same tree (Schopmeyer 1974). Both occur at the tips of small lateral branches, and both are formed as a result of the transformation of previously vegetative apices (Owens and Pharis 1971). Male and female strobili occur at different heights, however, and they differ in color. The reddish male strobili are borne on lower branches; the green female strobili occur near the treetops (Hedlin 1964, Søegaard 1969). The male strobili fall off after shedding the pink pollen. Pollen grains are single and spheroidal, without bladders, apertures, ridges, or folds. They are 20 to 45 $\mu$m in diameter and have scattered, isodiametric radial projections (see McAndrews et al. 1973). Western redcedar pollen does not preserve well, and it decays rapidly in peat bogs (Hansen 1941).

As the female strobili ripen, they change from green to yellow and finally to a pale cinnamon-brown (Schopmeyer 1974). Erect when young, they become reflexed when they reach their mature length of 13 mm (1/2 in) (Dallimore and Jackson 1967). Although immature female strobili may consist of up to 10 pairs of cone scales, only 5 or 6 develop to form the mature strobilus and, of these, only pairs 3 and 4 are fertile (Hedlin 1964). Two or three seeds are borne under each fertile scale (Bowers 1956).

Western redcedar seeds are chestnut brown and about 6 mm (1/4 in) long, with lateral wings about as wide as the body (Schopmeyer 1974). Approximately 9.65 g of cleaned seed are obtained per liter of cones (0.75 lb of seed per bushel). Schopmeyer's 1974 data summary shows 448,000 to 1,305,000 cleaned seeds per kilogram (203,000 to 592,000 seeds per pound).

## Roots

The roots of western redcedar may be recognized by their extremely thin brown outer bark, which is underlain by a thin pink to purple-red zone above the white inner bark. Young roots may have a thick, white, pulpy outer layer outside the pink zone (Gilbertson et al. 1961). The tap roots are poorly defined or nonexistent, but a profuse fine root system is developed (Leaphart and Wicker 1966). These small roots decay rapidly and lose most of their tensile strength within 3 to 5 years after the parent tree is felled. Larger redcedar roots may remain reasonably sound and intact for many years (O'Loughlin 1974).

Depth of root penetration was similar for western redcedar, Douglas-fir, and western hemlock where Eis (1974) excavated trees on Vancouver Island, but Smith (1964b) found redcedar roots to be shallower than those of Douglas-fir and deeper than western hemlock roots. Boyce (1929) mentioned the deep root system of western redcedar in explaining its windfirmness on the Olympic Peninsula. Jackson and Knapp (1914), Flint (1925), Hepting (1971), and Shinn (1971) refer to western redcedar as a shallow-rooted species, however, and Haig (1936) and Haig et al. (1941) found the root penetration poor. Where a thick duff layer is present, most redcedar roots occur in the duff rather than underlying soil (Ross 1932). Ross found no root hairs on these duff-inhabiting roots. Differences in local soil conditions probably are responsible for these various conclusions. Redcedar may form deep root systems on deep, moderately dry soils. Its root development is limited and shallow on wet sites (see Day 1957, McMinn 1960).

All authorities seem to agree that western redcedar has an extensive root system. Jackson and Knapp (1914) believed that bole buttresses indicated the number of principal roots, with masses of slender fibrous roots extending 3 m (10 ft) or more in all directions from the buttresses. The ratio of rootlet length to the length of the parent lateral root was 0.960 for the redcedars examined by Leaphart (1958) in northern Idaho. It was 0.260 for grand fir and only 0.005 for lodgepole pine. Leaphart and Grismer (1974) measured the extent of roots in a mixed-species stand in northern Idaho and found that western redcedar made up only 17 percent of the basal area but accounted for 82 percent of the root length.

Root grafting is more frequent in western redcedar than in Douglas-fir or western hemlock (Eis 1972). In addition to numerous small grafts, Eis found 27 grafts greater than 1 cm (0.4 in) in diameter between two redcedar trees growing on shallow soil over bedrock.

Western redcedar mycorrhizae are of the vesicular-arbuscular type (personal communication, James M. Trappe, Forestry Sciences Laboratory, Corvallis, Oregon).

### Bark

Western redcedar bark is light cinnamon-red or brown on young trunks, gray on old trees (Isenberg 1951). It is divided into wide ridges by irregular fissures that break up the surface into small plates (Dallimore and Jackson 1967). Redcedar bark is stringy (Wethern 1959) and, even on old trees, thin. It varies from 1.3 to 2.5 cm (1/2 to 1 in) thick (Sudworth 1908, Isenberg 1951, Bowers 1956, Dallimore and Jackson 1967). It is slightly heavier than the wood, weighing 0.37 to 0.39 g per $cm^3$ (23.1 to 24.3 lbs per $ft^3$) (see Smith and DeBell 1973, Brown et al. 1977).

Stem bark accounted for about 19 percent of the aboveground weight of 5- to 15-cm (2- to 6-in) d.b.h. trees measured by Smith and DeBell, 10 percent of the weight of 30- to 41-cm (12- to 16-in) d.b.h. trees. About 6 percent of the aboveground weight of 23- and 41-cm (9- and 16-in) d.b.h. redcedars measured by Grier and Logan (1977) consisted of stem bark. Smith et al. (1961a) found redcedar bark percentages to be slightly lower than those of western hemlock, much lower than the bark percentages of Douglas-fir. When Brown et al. (1977) compared bark and stem volumes in Montana and Idaho, they found the bark volume/stem volume ratio lower in western redcedar (0.15) than in ponderosa pine (0.24), white pine (0.21), Douglas-fir (0.19), western larch (0.24), or western hemlock (0.18). When they compared bark weight to stem weight, the redcedar bark proportion (0.173) was smaller than that for all other conifers except lodgepole pine (0.114).

For similar tree sizes, redcedar bark is slightly thinner than western hemlock bark at the top of the first 4.9-m (16-ft) log in southeastern Alaska. It is slightly thicker than Sitka spruce or Alaska-cedar bark measured at that point (see Bones 1962). Bark thickness varies among trees, but the inner bark of western redcedar tends to be thinner than that of Sitka spruce and its outer bark tends to be thicker. Redcedar bark has less airspace, lower moisture content, and a higher specific gravity than Sitka spruce bark (see Smith and Kozak 1971).

Western redcedar has a brown first periderm and a reddish purple secondary periderm (Mullick 1971). The purple color is a property of the nonanthocyanic phlobaphene pigments found there (Mullick 1969a). One of these phlobaphenes was analyzed and described by Swan (1963a). Anthocyanidins are also present in the secondary periderm (Mullick 1969b). The inner and outer bark are similar, but outer bark has a higher lignin content (Cram et al. 1947). The lignin from the outer bark differs from that of the inner bark and from most other softwoods in that it contains fewer methoxyl groups and aromatic protons, more catechol groups, and more aliphatic protons (Swan 1966).

Compounds that have been extracted from western redcedar bark include:

arachidic acid (Fraser and Swan 1978)
aspartic acid (Swan 1963b)
campesterol (Fraser and Swan 1978)
catechin (Swan 1963b)
D-fructose (Swan 1963b)
D-glucose (Swan 1963b)
diethyl octadecanedioate (Swan 1968)
docosanoic acid (Fraser and Swan 1978)
eicosanoic acid (Fraser and Swan 1978)
epicatechin (Swan 1963b)
ethyl 18-hydroxystearate (Swan 1968
ferulic acid (Swan 1968)
isopimaric acid (Fraser and Swan 1978)
leucocyanidins B and C (Swan 1963b)
myristic acid (Fraser and Swan 1978)
19-norisopimara-8(14), 15-dien-3-one (Fraser and Swan 1973)
norditerpene alcohols (Quon and Swan 1969)
oleic acid (Fraser and Swan 1978)
palmitic acid (Fraser and Swan 1978)
p-hydroxyphenylpyruvic acid (Swan 1963b)
shikimic acid (Swan 1963b)
stearic acid (Fraser and Swan 1978)
sucrose (Swan 1963b)
tannins, oils, and waxes (Smith and Kurth 1953)
taxifolin glucoside (Hergert and Goldschmid (1958)
terpinen-4-ol (Fraser and Swan 1978)
tetracosanoic acid (Fraser and Swan 1978)
thujone (Fraser and Swan 1978)
xanothoperol (Fraser and Swan 1978)

When Smith and Kurth (1953) analyzed several western redcedar trees near Oakridge, Oregon, they found that extractive contents of the bark were higher in treetops than in butt logs, ranging from 18 to 29 percent. In contrast, calcium content of western redcedar bark increases with distance from the treetop (Webber 1973).

## Wood

Stem wood made up 57 to 73 percent of the aboveground weight of the western redcedar trees measured by Smith and DeBell (1973) and 70 percent of the two redcedars measured by Grier and Logan (1977). The wood is coarse and straight grained with a characteristic sweet odor and faint bitter taste (Brown et al. 1949, Isenberg 1951, Forest Products Laboratory 1955). The green heartwood has an average moisture content in North America of 58 percent — about the same as the moisture content in the heartwoods of western larch, western white pine, Pacific silver fir, Engelmann spruce, and Port-Orford-cedar (see Forest Products Laboratory 1955). Western redcedar heartwood grown in New Zealand is very wet in many trees, however, and heartwood moisture content up to 298 percent has been recorded there (Harris and Kripas 1959). The average moisture content of green redcedar sapwood in North America is higher than that of any other conifer — 249 percent (see Forest Products Laboratory 1955).

North American western redcedar wood weighs 0.37 to 0.38 g/cm$^3$ (23 to 24 lb/ft$^3$) when air dried, 0.31 to 0.34 g/cm$^3$ (19.5 to 21.0 lb/ft$^3$) when ovendried (Desch 1948, Isenberg 1951, Forest Products Laboratory 1955, Higgins 1957, Smith and DeBell 1973). Weight per unit volume (density) of western redcedar wood varies with its position in the tree, increasing with height and decreasing from pith to cambium (Wellwood and Jurazs 1968, Okkonen et al. 1972). Wood density also varies with geographic location and site. Western redcedar in Montana and Idaho is less dense than all other western conifer woods except that of subalpine fir (see Brown et al. 1977). Densities of commercial redcedar wood are similar in Oregon and British Columbia — 55 percent and 56 percent that of Douglas-fir. The "scrub" redcedars of British Columbia have denser wood, however — 71 percent of Douglas-fir density (Wethern 1959). A survey of densities of western woods (Maeglin and Wahlgren 1972) showed great variation, with average specific gravities of western redcedar ranging from 0.318 in western Washington to 0.357 in Montana. Western redcedar wood grown in Germany is denser (0.37 g/cm$^3$) than that grown in North America (see Volkert 1956). The German values decreased as annual ring widths increased — from 0.4 g/cm$^3$ with 2-mm rings to about 0.28 g/cm$^3$ with 8-mm rings.

Annual growth rings are distinct in western redcedar. Transition from springwood to summerwood within each annual ring is more or less abrupt, and the summerwood is narrow and hard (Brown et al. 1949, Isenberg 1951, Forest Products Laboratory 1955). Resin canals are absent. Metatracheal parenchyma is present, but very variable in distribution. Rays are uniseriate and 1 to 12+ cells high, with some gummy infiltration of the ray cells (Brown et al. 1949, Johnston 1951). Ray tracheids are occasionally found on the upper and lower margins (Brown et al. 1949, Kobayashi 1956). Tracheids have one to two rows of bordered pits on the radial walls (Brown et al. 1949). The membranes of these bordered pits do not possess a torus, but consist of numerous, closely packed strands (Krahmer and Cote 1963).

Average tracheid diameter of western redcedar decreases with increased latitude, altitude, and tree age in Idaho (Crooks 1964). Redcedar tracheids in British Columbia are shortest near the stump. They reach maximum length about midheight in the tree and decrease slightly thereafter (Wellwood and Jurazs 1968). Wellwood and Jurazs found that tracheid length increased from the pith outward in redcedar wood. When the wood is macerated to make kraft pulp, western redcedar fibers average shorter (2.05 mm) than either western hemlock (2.21 mm) or Douglas-fir (2.62 mm) fibers (Graff and Isenberg 1950). Summerwood fibers of western redcedar are unique in that increasing tensile strength is associated with a decreasing Young's modulus (Jayne 1960).

Other stress limits and strength properties of western redcedar wood are listed by Newlin and Wilson (1917), the West Coast Lumber Trade Extension Bureau (1927), the Forest Products Laboratory (1955, 1963), and Bendtsen (1972). Their data show that the ends of western redcedar are harder and more difficult to crush than the ends of western white pine and sugar pine, but its sides are softer and easier to crush. Redcedar shear strength is low. Volumetric shrinkage and thermal conductivity are also low, however; western redcedar has the lowest volumetric shrinkage listed by Higgins (1957) and the lowest thermal conductivity of any softwood listed by the Forest Products Laboratory (1955). Its thermal emissivity is approximately 0.91 (Owens 1964). The low tangential shrinkage of redcedar seems to be the result of a low summerwood percentage in the annual rings, plus relatively low shrinkage of both springwood and summerwood (Erickson 1955). Its longitudinal shrinkage, though low, is greater than those of western hemlock and the true firs (Espenas 1974).

Western redcedar is a soft, stable, weak wood that splits easily and is not very tough. Toughness is increased by extracting extraneous compounds with an alcohol-benzene mixture (Raczkowski 1968, Lawniczak and Raczkowski 1970).

Toughness and strength seem to vary with redcedar wood color. Dark brown heartwood is less tough, softer, and weaker than lighter colored heartwood (Findlay and Pettifor 1941). This dark brown heartwood usually occurs near the center of the tree and is surrounded by a narrower red-stained layer inside an outer zone of straw-colored heartwood (van der Kamp 1975). Redcedar sapwood is white and narrow, generally 2.5 cm (1 in) or less wide (Lutz 1972). It is wider than western larch sapwood, narrower than the sapwoods of Engelmann spruce, Douglas-fir, lodgepole pine, or ponderosa pine (Lassen and Okkonen 1969). Krahmer and Cote (1963) found the air-permeability ratio of early sapwood to late heartwood to be 6.5 in redcedar — lower than in Douglas-fir or western hemlock. Redcedar heartwood pH (3.0 to 3.4) is lower than sapwood pH (4.1 to 4.7) (van der Kamp 1975). Although western redcedar has a lower pH than most species (see Farmer 1962), the wood acts as a pH buffer when suspended in water (Carroll et al. 1973).

The identification of heartwood and sapwood is usually relatively easy for western redcedar. Nevertheless, application of perchloric acid, Benedict's solution, Fehling's solution, or ammonium bichromate may be useful in difficult cases (Brown and Eades 1948, Eades 1958). The usual heartwood-sapwood orientation is absent in some southeastern British Columbia redcedars, where a target-shaped pattern of alternate concentric bands of light- and dark-colored wood occurs (MacLean and Gardner 1956b). The dark heartwood bands are rich in natural preservatives. Very dark oil or resin streaks are even richer in preservatives when they occasionally occur in western redcedar heartwood (Gardner 1963).

Natural preservatives comprise one of the most important and interesting characteristics of western redcedar. About 10 percent of the total heartwood consists of extractives (Gardner 1963), and up to 23 percent extractive content has been found in some portions (MacLean and Gardner 1956a). Indeed, 30 to 50 percent extractive content sometimes occurs in the resin streaks (Gardner 1963).

A complete list of the many organic compounds in redcedar wood would be long. The six most important compounds isolated from volatile oils and their approximate percentages in butt heartwood are listed below (see Anderson and Gripenberg 1948; Erdtman and Gripenberg 1948a; Rennerfelt 1948; Gardner and Barton 1958a, 1958b; Roff and Whittaker 1959; Wethern 1959; Lyr 1961; and Gardner 1963):

| | |
|---|---|
| α-thujaplicin | 0.01 percent |
| β-thujaplicin | 0.30 percent |
| γ-thujaplicin | 0.20 percent |
| β-thujaplicinol (7-hydroxy 4-isopropyltropolone) | 0.07 percent |
| thujic acid | 0.08 percent |
| methyl thujate | 0.17 percent |

Polyphenolic lignans may not be as important, but they make up the major portion of the heartwood extractives (see MacLean 1970). Eleven of these lignans have been identified and described (Gardner et al. 1960, 1966; MacDonald and Swan 1970; MacDonald and Barton 1973; Kirbach and Chow 1976): thujaplicatin, dihydroxy thujaplicatin, thujaplicatin methyl ether, hydroxy thujaplicatin methyl ether, dihydroxy thujaplicatin methyl ether, γ-thujaplicatene, plicatic acid, plicatin, plicatinaphthalene, plicatinaphthol, and β-aploplicatitoxin.

Thujaplicatin and the thujaplicatin methyl ethers are also present in much smaller concentrations within the sapwood. They build up slowly there, then increase dramatically at the sapwood-heartwood boundary (Hillis 1968, Swan et al. 1969, MacLean 1970). Treatment with enzyme inhibitors may increase the amounts of thujaplicatin, thujaplicatin methyl ethers, and β-sitosterol produced in sapwood (see Swan 1971).

Other western redcedar wood constituents include β-dolabrin (Gardner and Barton 1958a, Gardner 1963), nezukone (Hirose and Nakatsuka 1967), cumic acid (Barton and MacDonald 1971), unnamed soluble and insoluble phenols (Barton and Gardner 1954, Krueger 1968), and various hemicelluloses (Lewis 1950, Hamilton and Partlow 1958). Western redcedar hemicelluloses are similar to those of other conifers, except that the xylan contains a lower percentage of L-arabinose (Dutton and Funnell 1973). Western redcedar wood has a high lignin content (Lewis 1950) — higher than the woods of western hemlock, Douglas-fir, and Engelmann spruce (Wilson et al. 1960). More nonreducing sugars than reducing sugars are present in the sapwood (Radwan 1969).

Thujaplicin and water-soluble phenol increase in redcedar heartwood with distance from the pith, decrease with height (MacLean and Gardner 1956a, Tickle 1963). Calcium and potassium in the wood increase with height (see Webber 1973).

Soluble phenols apparently leach out of redcedar wood when fresh logs are stored in water. Kiser and Griel related the periodic absence of plankton from millponds to the presence of freshly cut western redcedar logs in those ponds.[8/] Their subsequent laboratory experiments indicated that steam-distilled redcedar oil from freshly cut old-growth sawdust was more toxic to copepods and cladocerans than either formalin or chloral hydrate.

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[8] Unpublished report, "The effect of red cedar oil on zooplankton organisms," by R.W. Kiser and J.V. Griel. 1956. On file, Centralia Junior College, Centralia, Washington.

The thujaplicins, dolabrin, and thujaplicinol ("tropolones") are toxic to coho salmon fry (Peters 1974, Peters et al. 1976) and guppies (Erdtman and Gripenberg 1948b). They are also largely responsible for the high natural durability of western redcedar wood (Barton 1973b). Variation in tropolone content therefore leads to variation in wood durability. Some cedar roofs last 50 years, for example, but others decay in less than 10 (Roff et al. 1962). The different moisture conditions associated with steep and flat roof pitches probably also contribute to these differences. Under similar conditions, redcedar wood deteriorates more slowly than the woods of western hemlock, Pacific silver fir, Sitka spruce, or Douglas-fir (Boyce 1929, Buchanan and Englerth 1940).

Cartwright (1941) and Englerth and Scheffer (1954) found the most durable western redcedar to be that nearest the base of the tree in the outer heartwood. The wood in large western redcedar logs is often exceedingly resistant to decay, and it sometimes remains sound after hundreds of years on the ground (see West Coast Lumber Trade Extension Bureau 1927). The fire resistance of western redcedar is poor (see Hall and Dell 1970), and moist heat reduces its decay resistance (Scheffer and Eslyn 1961).

## Uses and Properties

Western redcedar products have been important since prehistoric times. North American Indians, particularly tribes living along the coasts of Washington and British Columbia, used redcedar in many ways. Large logs were carved into totem poles and hollowed out to make huge ocean-going canoes. The redcedar logs were also split into wide planks used in building large timber frame structures that were often 15 m (50 ft) or more square (Vastokas 1969). Recent excavations of buried structures made by Indians have uncovered redcedar planks thought to be 6,000 to 10,000 years old (Sharpe 1974). Bark from young trees was used by the Indians to make baskets, ropes, blankets, mats, clothing, and thatch (see Sargent 1933, Bowers 1956, Dallimore and Jackson 1967, Bolsinger 1979). The flexible young branches were also used in making baskets. Thin twigs were woven into whaling ropes, and thicker ones were used for arrows (Edlin 1968). The roots were used for fishhooks (Dallimore and Jackson 1967).

Modern society also uses western redcedar in a variety of products. The wood is valued for canoe and boat construction, and redcedar is still being used to build timber frame structures — as exterior siding, shingles, sashes, doors, window frames, and interior finish (Forest Products Laboratory 1955, Wood 1959). In addition, western redcedar is used in utility poles, fenceposts, piling, paper pulp, clothes closets and chests, caskets, crates, boxes, beehives, rain gutters, and fish-trap floats (Butler 1949, Viereck and Little 1972, Sharpe 1974). A complete list would include many other products, for the wood is suitable for many uses.

Western redcedar wood is nonresinous, light, and easy to work (Forest Products Laboratory 1955, Wood 1959). It has exceptional dimensional stability and is a good thermal insulator (Forest Products Laboratory 1955, Tickle 1963). Redcedar wood glues easily, particularly with nonresin glues (Forest Products Laboratory 1955). Although naturally durable, it is difficult to impregnate with artificial preservatives — even by pressure processes (Titmuss 1965).

The ease of splitting redcedar is an advantage in the manufacture of handsplit shakes, but a disadvantage when trees are felled on rough hills and yarded with heavy machinery. Breakage, splitting, and shattering are often severe (McBride 1959). The wood is weak when used as a beam or post and low in shock resistance (Forest Products Laboratory 1955). The low density of redcedar was associated with poor fire resistance in the British standard fire-propagation test (Hall and Dell 1970). It is a soft wood that is extremely sensitive to marring (Packee 1976). The density and hardness of western redcedar can be increased threefold by using heat and pressure, without the addition of chemicals, but this is only a laboratory procedure of no commercial importance (Research News, Ottawa 1962a).

Western redcedar is one of the poorest woods for nail- and screw-holding capacity. It is also poor for bolt-holding and is one of the weakest woods for withstanding connector loads (see Forest Products Laboratory 1955, Hokhold 1965). Special ring-shanked nails improve the nail-holding capacity of redcedar (Lee and Lord 1960), and increasing the screw lengths by 0.6 cm (1/4 in) improves its screw-holding properties enough to equal those of western hemlock, Scotch pine, and Norway spruce (British Columbia Lumber Manufacturers Association, n.d.)

Dry western redcedar takes and holds stains, paints, enamels, and clear finishes very well (West Coast

Lumber Trade Extension Bureau 1927, Wood 1959, Jones 1966). It ranks with redwood as the best paint substrate available in North American woods (Gardner 1963). Lack of extreme differentiation between springwood and summerwood, plus low summerwood swelling and the resulting lack of raised grain, seem to be responsible (see Brown 1957, MacLean 1970). Blistering is serious where free water (not just water vapor) is present behind the paint film in western redcedar, however; more serious than in Douglas-fir, Alaska-cedar, white pine, red pine, or spruce (Veer and King 1963). Extractive globules became concentrated on the paint surface in the 100-percent humidity maintained by Veer and King. Extractive bleedthrough can be a problem (Forest Products Laboratory 1966, MacLean 1970).

One of the best clear finishes for western redcedar wood is a tung oil modified, phenolformaldehyde-resin-based varnish (Oliver 1957). The best pigmented, penetrating stain seems to be the Forest Products Laboratory natural finish (60 percent linseed oil, 5 percent pentachlorophenol, 10 percent pigment, 0.3 percent zinc stearate, 1.0 percent wax, and 3.7 percent volatiles); the best water-soluble inorganic salt finishes contain acid copper chromate, chromated copper arsenate, or copper-pentachlorophenol (Grantham et al. 1976). When left unfinished, western redcedar weathers gray (Wood 1959) and resists decay, but erodes appreciably faster than redwood, Douglas-fir, Engelmann spruce, or ponderosa pine (Feist and Mraz 1978). Both western redcedar and redwood weathered better than Monterey pine, alpine-ash, Brisbane boxwood, or King-William-pine in Australia (Woodhead 1969). Redcedar wood is quite resistant to corrosion by hydrochloric acid but is less suitable than baldcypress or longleaf pine for use in contact with acids (American Wood Preservers Association 1946).

## Prices

The many uses and excellent properties of western redcedar products have increased the demand for them in recent years. This increasing demand has been accompanied by accelerating price increases. Both consumption rates and prices have increased more rapidly for western redcedar products than for products of most other west coast woods (Bolsinger 1979). Western redcedar and Alaska-cedar commanded average round-log values higher than any other Alaska tree species in 1971 (Farr and LaBau 1971).

In western Washington and northwestern Oregon, the average price paid for all western redcedar logs increased from $57.30 per thousand board feet in 1965 to $320.80 per thousand board feet in 1977 — an average annual increase of 15.4 percent compared with average annual price increases of about 12 percent for Douglas-fir and western hemlock during the same period (Bolsinger 1979). The accelerating nature of these price increases is emphasized by Ruderman's (1978) calculations for 1975-77; average annual increases in log price were 35.1 percent for western redcedar, 20.0 percent for Douglas-fir saw logs, and 13.2 percent for western hemlock. As the estimated annual harvest of western redcedar in the United States for 1975 to 1976 was 950 million board feet (Bolsinger 1979), such price increases represent very large sums spent for redcedar products.

Accelerating price increases and an increasing demand for redcedar products may stimulate greater use of defective western redcedars like those found in the extensive stands of decadent cedar and hemlock in interior British Columbia. Dobie (1976) concluded that rehabilitation of these decadent stands could be profitable only at very low discount rates for short rotations on good and medium sites, but subsequent price increases may provide economic alternatives.

## Lumber

Lumber was the chief western redcedar product in Oregon, Montana, and Idaho in 1976 (Bolsinger 1979). Most redcedar logs used for lumber manufacture are acceptable in terms of eccentricity, sweep, taper, and shake (see Packee 1976). Redcedar lumber cut from these logs is easy to kiln dry, but boards from the butt log (Desch 1948) and thick planks (Forest Products Research Board 1950a) sometimes collapse during drying The cell walls are distorted or obliterated, and redcedar lumber does not recover after collapsing (Tiemann 1941). Predicting collapse from the appearance of a log is difficult or impossible, but collapse is associated with higher than normal extractive content (Meyer and Barton 1971, Barton 1975). Most redcedar logs subject to collapse seem to come from low or swampy ground (Guernsey 1951). Guernsey observed that heavy boards were more likely to collapse than light ones. He recommended air drying before kiln drying or, if this is impossible, initial kiln temperatures that do not exceed 49 °C (120 °F).

Kiln temperatures above 100 °C (212 °F) with three to six times shorter drying times have been tested, but they resulted in nonuniform moisture content and a 5-percent loss of bending strength in western redcedar (Ladell 1953). Less severe, moderately accelerated drying schedules can be successfully used with lightweight boards of less than 45-percent moisture content (Salamon and Hejjas 1971). Kiln drying does not destroy the heartwood extracts of redcedar, but it makes them more soluble (Sowder 1927). Kiln corrosion should be considered when western redcedar is dried, because the thujaplicins are steam-distillable; they sometimes condense on metal kiln parts and corrode them (Barton 1972).

Extractive-caused metal corrosion occurs even without the high temperatures associated with kiln drying. The zinc and lead used in roof gutters and valleys are sometimes corroded by rainwater extracts from western redcedar shingles or shakes (Forest Products Research Board 1950b). Iron, steel, copper, and brass fasteners (such as nails, screws, hinges) often corrode when in contact with redcedar lumber (see Campbell and Packman 1944, Farmer 1962, Titmuss 1965). The carbide-tipped saws and knives used in lumber manufacture also are corroded, dulling much sooner when used on unseasoned western redcedar than when used on other woods (Kirbach and Chow 1976). Recommended remedies include substituting another metal for the cobalt in tungsten carbide and using aluminum or stainless steel nails, screws, and fittings (Research News, Ottawa 1962b).

Where lumber is used under moist conditions, as in water-cooling towers, western redcedar seems to be less suitable than redwood (see Western Australia Forests Department 1961). Nevertheless, untreated redcedar lumber had a service life of about 18 years in Canadian cooling towers (Roff 1964). When water-repellent treatments were applied to western redcedar, waxes and wax solutions gave the most durable results (Gray and Wheeler 1959). Western redcedar responded better than eastern redcedar or baldcypress to waxing and staining treatments used in the preparation of pencil slats (Greaves and Harkom 1949).

Redcedar is the most important western species used for siding in the United States and Canada (Panshin and deZeeuw 1970), and it shows promise as a homegrown lumber species in Great Britain (Priest 1974). It is suitable for pattern making in foundries (Hale 1954). Redcedar makes excellent horticultural boxes (Moore and Bryan 1946) and is used in greenhouse construction (Syrach Larsen 1943). Western redcedar is unsuitable for apple boxes, however; the apples absorb volatiles from the wood and spoil (Ministry of Agriculture, Belfast, n.d.; Colhoun et al. 1961; Colhoun and Park 1963; Loughnane and Gallagher 1963).

## Shakes and Shingles

Shakes and shingles are the chief western redcedar products in Washington, and British Columbia exported 3,294,000 squares in 1978.[7] Recent increases in shake and shingle production have been greater than the production increases in other redcedar products (Bolsinger 1979). Even before those increases, more than 95 percent of all wooden shingles manufactured in the United States were made from western redcedar (Brown and Panshin 1940). Attractive appearance, durability, lightness, and superior insulation probably are responsible for the popularity of redcedar as a roofing material. The insulating properties of 2.54 cm (1 in) of western redcedar wood are equal to 30 cm (12 in) of concrete or 19 cm (7.5 in) of brick or clay tile (O'Hea 1947).

Three types of redcedar shakes are manufactured: Straight split, taper split, and handsplit-resawn. All come in random widths of 10 to 30 cm (4 to 14 in). Lengths range from 46 to 81 cm (18 to 32 in), but the 61-cm (24-in) length is most common (The Lumberman 1957). Straight-split and taper-split shakes are both handsplit from redcedar blocks, but the blocks are reversed every other time for taper-split shakes. Handsplit-resawn shakes, which account for most of the shake production, have a coarse-textured split surface on one side and a smooth sawn surface on the reverse side (Munger 1970).

Only old, slow-growing, straight-grained, relatively knot-free western redcedar trees seem to be suitable for shake manufacture. Good shake material has 35 to 50 annual rings per inch (14 to 20 rings per cm). At least 245 years are required to produce a tree of suitable size for such material, and the shake industry is supported by redcedar trees that are 500 to 1,500 years old (Munger 1970). Such trees probably constitute a nonrenewable resource when considered in the scale of human time (see Munger 1970, Mitson and Holman 1975).

Younger trees may be suitable for redcedar shingles (Packee 1976). The two types of western redcedar shingles are slash grain and edge grain. Edge-grain shingles do not curl and are more durable (O'Hea 1947). Although untreated redcedar shingles may last for 25 years in Pennsylvania (Fergusson 1938) and 50 years in Washington (see Grondal 1913), they are less durable than redwood shingles in the wetter parts of Honolulu (Skolmen 1968). Leaching of the water-soluble heartwood extractives in wet conditions may be responsible (see Cserjesi 1976), but the low pitch of modern roofs also reduces durability.

Pressure impregnation with copper, chromium, and arsenic preservatives improves the durability of redcedar shingles (Smith 1964b). Impregnation with leach-resistant fire retardants makes the shingles more fire resistant (St. Clair 1969, Holmes 1971, Juneja 1972). Amino-resin-forming compounds are effective retardants (King and Juneja 1974).

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[7] This statistic was obtained from the Council of Forest Industries of British Columbia, Vancouver. A "square" is the amount of shingles or shakes required to cover an area of 9.29 m² (100 ft²), exclusive of overlap.

High-temperature kiln-drying schedules can be used to bring unbundled western redcedar shingles from green to shipping weight in less than 2 hours (see Salamon 1960). Shingle durability is not appreciably affected by these high-temperature schedules (MacDonald and MacLean 1965).

## Poles and Piling

Good form, large size, light shipping weight, easy climbing-spur penetration, and durability make western redcedar an excellent species for pole production, but it has a tendency to crush when used as piling (Brown and Panshin 1940). Redcedar poles taper more than southern pine or Douglas-fir poles (Bohannan et al. 1974). They are remarkably consistent in strength, however, showing no significant differences between geographic locations, elevations, or seasoning treatments (McGowan and Smith 1965).

Western redcedar poles constitute a plentiful renewable resource in British Columbia. Anderson (1961) estimated a provincial supply of about 121 million poles. Without considering annual growth, he forecast a pole supply of 300 years at the 1961 cutting rate of 400,000 poles per year. Approximately 200,000 poles were cut each year in the United States, which consumed about 400,000 redcedar poles annually (Anderson 1961).

Average-size western redcedar poles with sapwood less than 2.54 cm (1 in) thick should last about 12 to 17 years without treatment (Forest Products Laboratory 1955). More than half the untreated redcedar telephone poles on the Island of Hawaii were still serviceable after 20 years, however (Boone 1965). When in contact with the ground, they have a service life proportional to their diameter, not their cross-sectional area (Purslow 1962).

The service life of redcedar poles has been increased through several preservative treatments. Spraying freshly peeled green poles with urea minimized the checking that sometimes occurs during drying (West Coast Lumberman 1941). The dry poles were pressure treated with creosote and creosote-coal tar solutions during the 1940's (American Wood Preservers Association 1943, 1944). Hot- and cold-bath treatments with creosote and pentachlorophenol were then tried (see Colley 1946). Preservative penetration was often poor in western redcedar poles, however, and it varied with position and wood condition within a single pole (Jurazs and Wellwood 1965). Fortunately, the portions with poorest penetrability seemed to have the highest extractive content and least need for preservative treatment. Nonpressure treatment — such as butt-soaking or soaking the entire length of the pole — is common now. Pressure treatments are less used — the redcedar poles tend to become oversaturated (Randall and Sutherland 1974).

Redcedar poles are seldom retreated now, but several formerly used procedures for re-treating in-service poles are of historical interest. One method was machine-shaving the sapwood and subsequently soaking the shaved pole in creosote (Lyon 1939). A somewhat similar procedure was used on redcedar bridge piling. After removing soil from around the affected portion, decayed wood was scraped off and the piling treated with a gelatinous suspension of NaF dinitrophenol and potassium dichromate (Railway Track and Structures 1955). Aboveground sap rot in redcedar poles has been treated by spraying with a 10-percent solution of pentachlorophenol (Graham and Wright 1959, Scheffer and Graham 1973).

Green or wet western redcedar power poles — particularly wet poles that have been in saltwater — may have low electrical resistances that are potentially hazardous to line workers (see Katz and Miller 1963, Breeze and Vitins 1965).

## Pulp

The low density of western redcedar is the most serious handicap to its increased use in pulping (Wethern 1959). Pulp is produced and sold by weight, but the logging and lumber industries work by volume. Because a given volume of western redcedar contains only 77 percent as much wood by weight as the same volume of western hemlock and only 66 percent as much as the equivalent volume of Douglas-fir, the redcedar produces less pulp (Wethern 1959). Low lignin and extractive contents are highly desirable for chemical pulping processes — but western redcedar wood has relatively high contents of both (see Packee 1976).

The stringy redcedar bark is difficult to remove with standard debarking equipment. Chemical debarking with sodium arsenate has been tried successfully (DeMoisy 1952); ingrown bark is difficult to remove by any debarking technique, and it may create problems in some chemical pulping processes. Pilot-plant studies indicated that redcedar bark could be processed satisfactorily, however, and even whole-log chipping was possible (Thomas and Davis 1974).

The sulfate process is most frequently used to produce pulp from western redcedar. Yields are lower in sulfate than sulfite pulping, increasing the disadvantage of redcedar density mentioned earlier (Wethern 1959). The acidic constituents of western redcedar wood consume extra alkali, further reducing profits in a sulfate pulping operation (see Thomas and Davis 1974). Redcedar extractives corrode the steel ordinarily used in digesters and recovery equipment, sometimes reducing digester life by 50 percent compared with digesters used for western hemlock or Douglas-fir

(Wethern 1959, Thomas and Davis 1974). The life of evaporator tubes may be reduced by 80 percent (see Gardner 1963). Thujaplicins, a phenolic constituent, or both probably are responsible (British Columbia Lumberman 1953, MacLean and Gardner 1953a). Redcedar pulp drains poorly, sometimes restricting production even further (Thomas and Davis 1974). Its color constitutes a final handicap (Troxell 1954); redcedar pulp bleaches with difficulty (Isenberg 1951).

Some handicaps of redcedar pulping have been turned into advantages by skillful manipulation of the sulfate process, and redcedar has some favorable pulping characteristics. For example, adding 3 to 5 percent sodium sulfide to the cooking liquor offsets the deleterious effects of high alkalinity and improves both the yield and strength of redcedar pulp (Christiansen et al. 1957). Western redcedar requires a shorter sulfate-process cooking time than other British Columbia species (Wilson et al. 1960). It has finer fibers than western hemlock, Douglas-fir, or southern pine and makes a dense sheet with good opacity (Murray and Thomas 1961). Indeed, bleaching sulfate pulp made from western redcedar sawdust yields a product with an opacity comparable to hardwood pulps (Proctor and Chow 1976). The fine fibers tend to be shorter than those in Douglas-fir pulp (Heinig and Simmonds 1948, Graff and Isenberg 1950), but western redcedar pulp does not differ chemically from the sulfate pulps of Douglas-fir, western hemlock, black spruce, or loblolly pine (Lewis et al. 1950).

Physically, redcedar pulp has several desirable attributes. Unlike Douglas-fir, western hemlock, or Pacific silver fir, western redcedar produces very good kraft (sulfate) pulp (see Packee 1976). This pulp has high bursting, folding, and tensile strengths that offset its low tearing strength (see Bray and Martin 1947, Holzer and Booth 1950, Wethern 1959, Wilson et al. 1960, Murray and Thomas 1961). Western redcedar pulp has a high specific surface area (Browning and Baker 1950). Its cellulose characteristics are similar to those of western hemlock and loblolly pine pulps (see Clark 1950, Heuser et al. 1950). Sulfate pulp made from redcedar bark has lower bursting and tensile strengths, higher tearing strength than that made from wood (Thomas and Davis 1974).

Although sulfite pulp yields are higher than sulfate (kraft) yields for western redcedar (see Packee 1976), redcedar requires a longer cooking time and more chemicals than western hemlock in the sulfite process. The resulting low-brightness cedar pulp drains poorly (Wethern 1959). Redcedar sulfite pulp is dark and difficult to bleach (Isenberg 1951), and the use of a bisulfite cooking liquor with a high magnesium content seems necessary (see Keller and McGovern 1945). The bursting strength of western redcedar sulfite pulp is relatively high in comparison with the sulfite pulps of other species. Its tear strength is relatively low (see Holzer and Booth 1950).

Mechanical (groundwood) pulping processes are not practical for western redcedar (Wethern 1959). The resulting product has very good strength and printing qualities but poor brightness (see Packee 1976). Semichemical redcedar pulps may be useful in making paperboard (McGovern et al. 1951).

## Veneer and Plywood

Western redcedar is highly suitable for decorative face veneer, but unsuitable for the inner plies of decorative veneer or for use in container material (see Packee 1976). Packee rated redcedar veneer logs as excellent when assessed for freedom from reaction wood, resin or gum, and bark pockets. Redcedar logs were rated "acceptable" when assessed for freedom from decay, knots, and wet wood.

Western redcedar plywood panels can be made by slicing the logs and cold pressing the resulting veneer (West Coast Lumberman 1946). Where hot pressing is used, high glue spreads and press temperatures of 270°F (132°C) or lower have been recommended to prevent blistering (Carstensen 1961). Although highly rated for decorative plywood (Lutz 1972), redcedar is too weak for construction grade structural plywood (Palka and Warren 1977).

## Waste Utilization

Redcedar lumber, shake, and shingle manufacture produces tremendous quantities of waste material. Logging residue in some clearcut redcedar stands may average 238 $m^3/ha$ (3,400 $ft^3/acre$) (Howard 1973). The residues produced annually from cedar sawmills in Oregon, Washington, and British Columbia were estimated to be 1 to 1.5 million ovendry tons (907 to 1361 million kilograms) in 1968 (Scroggins and Currier 1971). Annual residues from shake and shingle mills were estimated to be 700,000 ovendry tons (635 million kilograms).

The average amounts of mill residues produced in western redcedar log processing are listed in table 5. Shake manufacture produces the least amount of waste, shingle manufacture the most. In shingle manufacture only a small portion of the original tree is marketed; slash and mill residues account for most of the original standing volume.

Much of the mill residue is suitable for pulp production (Bray and Martin 1947). It can also be used in fiberboard production if treated properly. Boards made from western redcedar bark alone tend to be unacceptably weak (see Schwartz 1949, Clermont and Schwartz 1948, Stewart and Butler 1968, Maloney 1973), but ozone treatment increases the bark's internal bond strength (Chow 1977b) and the addition of 10 percent sulfite pulp or sulfite screenings makes bark boards stronger (British Columbia Lumberman 1948). Boards made from wood components of the residue were acceptably strong (King and Bender 1951, 1952). Those made from sawdust, shingle tow (a stringy waste product resulting from shingle manufacture), or both were not (see Forest Products Laboratory, Canada 1949; King and Bender 1951, 1952).

Of all west coast conifer sawdusts, that of western redcedar is the only one that can be made into high quality, opaque pulp comparable to the hardwood sulfate pulps used in high-quality papers (Proctor and Chow 1976). It can be differentiated from the sawdusts of Douglas-fir, western hemlock, true firs, and the spruces with a color test using chloroform and ferric chloride (Barton 1973a). Redcedar sawdust apparently decomposes more rapidly than Douglas-fir or western hemlock sawdust (see Bollen and Lu 1957). When not leached, it inhibits seed germination and seedling growth (Newton 1953) and damages Douglas-fir seedling roots (Krueger 1968). Redcedar sawdust makes a satisfactory rooting medium, however, when it is leached to remove the water-soluble extractives and mixed 3:1 with peat (Briggs 1973). Perhaps the most novel use of redcedar sawdust was as fill material where the trans-Canada highway crossed bogs and marshes (Southern Lumberman 1961).

Shingle tow has been used since about 1915 to keep tree seedlings moist during shipment. Krueger (1963, 1968) studied its effects on seedling survival and growth. He found that the thujaplicin extractives present in shingle tow were damaging to Douglas-fir seedlings but considered that the use of shingle tow was unlikely to cause heavy losses.

**Table 5 — Average amounts of mill residues produced in processing of western redcedar logs[1]**

| Product | Coarse residues | Fine residues | Total waste |
|---|---|---|---|
| | | *Percent of log volume* | |
| Lumber | 18 | 19 | 37 |
| Shakes | 14 | 14 | 28 |
| Shingles | 14 | 47 | 61 |

[1] From McBride (1959), Gardner (1963), Scroggins and Currier (1971).

## Extractives

Shingle tow, sawdust, and coarse residues are probably the best raw materials for producing most redcedar extractives (Wethern 1959). β-thujaplicin accumulates in digesters, evaporators, and kilns during redcedar processing, however, where it is readily available in commercially usable quantities (Trust and Coombs 1973). Potential uses of these extractives include insecticides, fungicides, antibiotics, chelating agents, catalysts, and perfumes (Wethern 1959).

Cedar leaf oil has been used in perfumes, insecticides, medicinal preparations, veterinary soaps, shoe polishes, and office deodorants (Forestry Abstracts 1965, Barton 1973b). It is a strongly scented, viscous liquid containing thujone, pinene, borneol, and borneol esters (Cochrane 1951, Bender 1963). Cochrane and Bender described the distillation procedure used to obtain this product. Steam extraction of freshly cut western redcedar leaves yielded 2.5 percent oil, based on dry leaf weight (Cochrane 1951).

Extractives probably were important in the successful production of fuel logs from wet redcedar sawdust (Gardner 1963). They were used to make a boiler-water additive that removed boiler scale and controlled foaming (British Columbia Lumberman 1951, McBride 1959). Water-soluble redcedar extractives have also been used in the electrolytic refining of lead (British Columbia Lumberman 1959). Even the lignin residue of *Poria asiatica* butt rot in western redcedar has been used — as a filler and extender in plywood glues (MacLean and Gardner 1953b).

Most of the extractives in western redcedar heartwood are formed from precursors at the sapwood/heartwood boundary (Swan et al. 1969). For example, nezukone is converted to thujaplicin at this boundary by hydroxylation of the tropone ring (Swan and Jiang 1970). The formation of different amounts of each extractive in older heartwood may be the result of changes in metabolism (more hydroxylation, less methylation) with aging (Hillis 1968).

## Medical Aspects

Although less potent than sodium-penicillin G and tetracycline hydrochloride, β-thujaplicin has been shown to inhibit the growth of a wide variety of bacterial species (Trust and Coombs 1973). It loses its antibacterial potency after irradiation by laboratory lighting (Coombs and Trust 1973).

Other western redcedar extractives seem to be more stable than β-thujaplicin. Southam (1946) found that water extract of redcedar heartwood inhibited the growth of bacteria and fungi even after the extract was boiled. It was inactivated by blood, serum, and cysteine. Large doses of redcedar extract did not cause death or illness in mice, and no *in vivo* activity against infection was demonstrated (Southam 1946). Both β- and γ-thujaplicins exert a combination of stimulant and depressant actions on the mammalian central nervous system, but the depressant component appears to be more predominant in β-thujaplicin (Halliday 1959).

Western redcedar allergies are frequently mentioned in the literature. Woods workers who handle redcedar sometimes develop dermatitis, conjunctivitis, or both (Ishizaki et al. 1971a, 1971b; Mitchell and Chan-Yeung 1974). Most of the dermatitis seems to result from contact with lichens and liverworts on the logs, however, and contact dermatitis from the redcedar itself is rare (Mitchell and Chan-Yeung 1974). Where dermatitis was caused by exposure to redcedar heartwood in a mill, γ-thujaplicin and 7-hydroxyisopropyltropolone appeared to be allergenic (Bleumink et al. 1973).

Allergic millworkers, carpenters, cabinet workers, construction workers, and wood carvers develop asthma or rhinitis after being exposed to western redcedar dust (Mitchell and Chan-Yeung 1974, Chan-Yeung and Grzybowski 1976). The allergy seems quite common (Gandevia 1970; Ishizaki et al. 1971a, 1971b; Shida et al. 1971; Mue et al. 1975; Chan-Yeung 1977). Symptoms are delayed, but persistent — nocturnal coughing and asthma for days or weeks after exposure (see Milne and Gandevia 1969, Gandevia and Milne 1970, Mitchell 1970, Chan-Yeung et al. 1971). Plicatic acid probably causes these symptoms (Chan-Yeung 1973, Chan-Yeung et al. 1973, Barton 1975).

## Insects

Western redcedars suffer little insect damage (Boyd 1959). Nevertheless, a considerable number of insects use redcedar as a host.

### Bark Beetles

The western cedar bark beetle (*Phloeosinus punctatus* LeConte) is widespread in the native range of western redcedar (see Boyd 1959, Canada Department of Agriculture 1959, Canada Department of Forestry 1960). Generally of little importance, it has been reported to kill trees sometimes (Furniss and Carolin 1977), but it usually occurs in felled or weakened trees (Isenberg 1951).

The redwood bark beetle (*P. sequoiae* Hopkins) is present on redcedars in coastal Oregon, Washington, British Columbia, and southeastern Alaska. In southeastern Alaska it is aggressive, attacking and killing western redcedar on poo sites (see Hard 1974, Furniss and Carolin 1977). *P. thujae* Perris attacks redcedars planted in the Netherlands (Doom 1964) and Germany (Kamp 1951).

### Wood Borers

The most damaging redcedar wood borer seems to be *Trachykele blondeli* Marseul, a flat-headed bore whose larvae mine the heartwood, causing degrade and cull in trees cut for products that require sound wood (Keen 1952, Boyd 1959, Furniss and Carolin 1977). Another flat-headed borer, *T. opulenta* Fall, also may occur in western redcedar (see Keen 1952).

Three round-headed borers mine the sapwood of native western redceda *Atimia confusa* Say (Furniss and Carolin 1977), *Semanotus amethystinus* LeConte (Boyd 1959, Furniss and Carolin 1977), and *S. ligneus* F. (Furniss and Carolin 1977). Ambrosi beetles *(Gnathotrichus sulcatus* LeConte, *Trypodendron cavifrons* Mannerheim, and other *Trypodendron* species) also work in western redcedar sapwood — but they seem to prefer Douglas-fir, western hemlock, or grand fir wood (see Johnson 1958).

The sapwood weevil *Hexarthrum thujae* Brown attacks overmature redcedar in British Columbia (Canada Department of Forestry 1960, Brown 1966, Furniss and Carolin 1977). Another sapwood weevil, *Rhyncolus brunneus* Mannerheim, breeds in dead redcedar wood (see Keen 1952, Canada Department of Forestry 1960, Furniss and Carolin 1977.) Insects of a third sapwood weevil genus *(Cossonus* spp.) live in decaying western redcedar, causing little or no economic damage (Keen 1952).

Other native western redcedar borers include a horntail, *Urocerus albicornis* F. (Furniss and Carolin 1977) and *Syntexis libocedrii* Rohwer, a wood-boring sawfly (Westcott 1971, Middlekauff 1974). European wood borers also attack western redcedar. *Xyloborus dispar* F. (an ambrosia beetle) is found on western redcedars growing in Germany (von Hennig 1954), and *Hylotrupes bajulus* L. (the oldhouse borer) can develop in redcedar wood grown in Poland (Dominik 1966). Redcedar siding on several British schools was riddled with the prepupal burrows of *Ametastegia glabrata* Fallén (a sawfly) after the wet summer of 1958 (Benson 1959).

## Defoliators

Seven loopers feed on western redcedar foliage:

*Lambdina fiscellaria lugubrosa* Hulst (Boyd 1959, Canada Department of Fisheries and Forestry 1969, Canada Department of the Environment 1974)

*Melanolophia imitata* Walker (Evans 1962, Dawson 1970)

*Ectropis crepuscularia* Denis & Schiffermüller (Canada Department of Fisheries and Forestry 1968, Furniss and Carolin 1977)

*Caripeta divisata* Walker (Furniss and Carolin 1977)

*Neoalcis californiaria* Packard (Furniss and Carolin 1977)

*Nepytia phantasmaria* Strecker (Furniss and Carolin 1977)

*Nepytia umbrosaria nigrovenaria* Packard (Furniss and Carolin 1977)

*Lambdina fiscellaria lugubrosa,* the western hemlock looper, is periodically destructive in coastal forests (Furniss and Carolin 1977). Its preferred host is western hemlock, but western redcedar is damaged when the loopers attack associated trees. *Melanolophia imitata,* the green striped forest looper, prefers humid areas (Furniss and Carolin 1977), where infestations sometimes cause serious defoliation of western redcedar and western hemlock (Dawson 1970). The saddleback looper, *Ectropis crepuscularia,* damaged redcedar trees in Alaska and British Columbia during 1951, 1953, 1960, 1961, and 1969. The other loopers listed above do not damage western redcedar significantly (see Furniss and Carolin 1977).

Nine nonlooper lepidopteran species occur on western redcedar foliage:

*Argyresthia cupressella* Walsingham (Keen 1952, Pettinger and Dolph 1967)

*A. thuiella* Packard (Van Frankenhuyzen 1974)

*Halisidota argentata* Packard (Sellars-St. Clare 1968, Furniss and Carolin 1977)

*Protoboarmia porcelaria* Gn. *indicataria* Walker (McGuffin 1943)

*Callophrys acuminata* Johnson (Johnson 1976)

*C. barryi* Johnson (Johnson 1976)

*C. byrnei* Johnson (Johnson 1976)

*C. plicataria* Johnson (Johnson 1976)

*C. rosneri* Johnson (Johnson 1976)

*Argyresthia cupressella,* the cypress tip moth, caused moderate redcedar defoliation on the Olympic Peninsula in 1966 (Pettinger and Dolph 1967). *A. thuiella* damaged western redcedar hedges in Holland during the winter of 1971-72 (Van Frankenhuyzen 1974). An outbreak of silver-spotted tiger moth *(Halisidota argentata)* occurred on southern Vancouver Island in 1954-55 (Furniss and Carolin 1977). The other species listed are not economically important.

## Seed and Cone Insects

Keen (1958) and Hedlin (1959) identified several insects of minor importance in western redcedar cones:

*Ptinus fur* L.

*Microgramme arga* Reitt.

*Eurytoma* sp.

*Torymus* sp.

*Amblymerus* sp.

*Tetrastichus* sp.

*Lestodiplosis taxiconis* Foote

The only major seed-damaging insect on redcedar seems to be a gall midge — *Mayetiola (Phytophaga) thujae* Hedlin (Hedlin 1959, 1964, 1974; Furniss and Carolin 1977). *Mayetiola* is a common pest, sometimes infesting 100 percent of the cones (Keen 1958, Hedlin 1964) and seriously damaging western redcedar seeds in Oregon, Washington, and British Columbia (Furniss and Carolin 1977).

## Miscellaneous Insects

Newly planted redcedar seedlings are sometimes damaged by the seedling weevil *Steremnius carinatus* Mannerheim) on cutover areas in British Columbia (Koot 1972), and another weevil *(Hylobius abietis* L.), attacks western redcedars in Poland (Ilmurzyński 1968). A cicada (*Melampsalta cingulata* Fabricius) seriously damaged the western redcedars planted in Waimiha State Forest, New Zealand (Ranger 1945).

Resistance of western redcedar wood to termites seems to vary with the termite species attacking it. Redcedar heartwood was not favored by *Reticulitermes flavipes* (Kollar) in a laboratory feeding test of 11 wood species (Carter and Smythe 1974). In feeding-choice tests of 21 commercial woods with *R. virginicus* Banks and *Coptotermes formosanus* Shiraki, however, western redcedar was among the least resistant woods tested (Mannesmann 1973). *Incisitermes minor* Hagen, the western drywood termite, preferred western redcedar heartwood to that of Douglas-fir, redwood, bald cypress, and Port-Orford-cedar (see Rust and Reierson 1977). It preferred redcedar sapwood to that of birch, Douglas-fir, oak, pine, redwood, or walnut. Another drywood termite, *Cryptotermes brevis* Walker, also preferred redcedar sapwood to the sapwood of Douglas-fir or southern yellow pine (Minnick et al. 1973). Redcedar heartwood lost much of its resistance to attack by *Reticulitermes lucifugus* Rossi after weathering in Germany (Arndt and Willeitner 1969).

## Extractives and Insects

Loss of extractives probably was responsible for decreased termite resistance after weathering in the German study. Although western redcedar wood is not particularly termite resistant, a neutral fraction of the volatile oil extracted from it is very effective against termites (MacLean 1970). Arndt (1968) found *Reticulitermes lucifugus* and *R. flavipes* to be adversely affected by the neutral oil fraction, unaffected by α- and γ- thujaplicins. *Incisitermes minor* preferred the extracts of walnut, Douglas-fir, sugar pine, redwood, and red oak to those of western redcedar — in almost reverse order to its preference for the woods from which these extracts were obtained (see Rust and Reierson 1977). The termite-repellent oil in redcedar, though effective when extracted, probably is present in inadequate quantities to protect redcedar wood from attack by most termite species.

Western redcedar sap probably is somewhat repellent to *Pissodes strobi* Peck, the Sitka spruce weevil. In laboratory bioassays, weevils preferred to feed on Sitka spruce sections soaked in water rather than on sections soaked in redcedar exudate (Vandersar and Borden 1977).

Volatile extractives of western redcedar wood apparently affect the choices of scolytid beetles for logs — they choose other log species (see Chapman 1963). Another volatile derived from redcedar, the N, N, diethylamid of thujic acid, is a potent mosquito repellant that surpasses the activity of standard repellants (Hach and McDonald 1971). Methyl thujate has some toxicity to carpet beetles and clothes moths, and its presence in cedar shavings used as litter probably controls poultry mites (Gardner 1963).

Wood extracts from western redcedar demonstrated juvenile-hormonelike activity on pupae of *Galleria mellonella* L. (Mansingh et al. 1970) and *Tenebrio* sp. (Barton et al. 1972). Similar activity occurred when larvae of the western tent caterpillar *(Malacosoma californicum* Packard *pluviale* Dyar) were treated with crude ether extracts of western redcedar (Wellington 1969).

# Diseases

Although Shaw (1973) lists 221 fungi that occur on western redcedar, the species is reputed to be less susceptible to pathological attacks than most of its associates (Boyd 1959). Nevertheless, most redcedars harbor pathogens. Redcedars live longer than their associates, and hollow old redcedar trees are common in the interior (see Daubenmire and Daubenmire 1968). Western redcedar is twice as defective as western hemlock and 20 times as defective as Sitka spruce in southeastern Alaska, where redcedars over 94-cm (37-in) d.b.h. average more than 50 percent cull (Klein 1951). Smaller trees also are affected. Half the coastal redcedar trees in the south-central portion of Vancouver Island have some decay by age 50; 100 percent have decay by age 450. In the interior, 80 percent of the redcedars are infected by age 150 and 100 percent have decay by age 290 (Buckland 1946).

## Seedling Diseases

Western redcedar seedlings are seldom damaged by damping-off fungi (Hepting 1971). They are resistant to *Phytophthora cactorum* Leb. & Cohn (see Vaartaja 1957b) and often undamaged by *Thelephora terrestris* Ehr. growth (Hepting 1971). Where redcedar seedlings are dense enough to shade the ground, however, *T. terrestris* sometimes smothers them (Weir 1921). Some redcedar seedlings are killed by the brown-felt snow mold (*Herpotrichia nigra* Hartig) in the Rocky Mountains (Hepting 1971). Other fungi that sometimes damage western redcedar seedlings include *Diaporthe lokoyae* Funk, *Seiridium cardinale* (Wagener) Sutton & Gibson, *Kabatina thujae* Schneider & v. Arx, and *Velutarina rufo-olivacea* (Alb. & Schw. ex Fr.) Korf (Funk 1974).

The major redcedar seedling disease — *Didymascella (Keithia) thujina* Durand — is a leaf blight that also occurs on older trees but is only serious on seedlings. When *Didymascella* reaches epidemic proportions, as much as 97 percent of the redcedar reproduction may be killed in its first season (Boyd 1959). Epidemics probably are rare in North America, however, and *Didymascella* is not as damaging there as it is in Europe (see Peace 1955, Søegaard 1969). Infection is rarely observed on 1st-year nursery seedlings in Europe, where major damage to nursery stock occurs during the 2d and 3d years (Søegaard 1966, Forestry Commission, London 1974). British attempts to avoid seedling damage by growing western redcedar in isolated nurseries (Peace 1955, 1958; Pawsey 1962b) succeeded at first, but eventually failed when those nurseries also became infected. Fortunately, diseased nursery seedlings sometimes recover after being planted out (see Keatinge 1948, Penistan 1966).

Effective control of *Didymascella* has been achieved by applying cycloheximide fungicides in British nurseries (Pawsey 1962a, 1965; Phillips 1962, 1964; Burdekin and Phillips 1971). Danish workers found that western redcedar cuttings are blight resistant (Søegaard 1954, 1956a).

## Foliage Fungi

The *Didymascella* leaf blight that attacks seedlings is the most important foliage disease of western redcedar. Blights caused by *Coryneum thujinum* Dearn. (Boyce 1961, Hepting 1971) and *Lepteutypa cupressi* (Nattrass, Booth, & Sutton) Swart (Canadian Forestry Service 1975) are much less important.

*Pestalotia funerea* Desm. is associated with redcedar dieback in Washington (Crops Research Division, Agricultural Research Service 1960). *P. peregrina* Ell. & Mart. caused a severe dieback of western redcedar in India (Sharma et al. 1973) and *Lophodermium juniperinum* (Fr.) DeNot. has been found on redcedar in Australia (Stahl 1966).

*Chloroscypha seaveri* (Rehm) Seav. has been associated with the death of western redcedar twigs (Ehrlich 1942), but the twigs probably were killed by other organisms (Gremmen 1963). Other fungi inhabiting dead or senescent redcedar foliage include *Sphaerella canadensis*, Ell. & Ev., *Mycosphaerella thujae* Petr., and *Microthyrium thujae* Dearn. (Hepting 1971). *Limacinia alaskensis* (Sacc. & Scalia emend Barr.) causes a minor surface mold in cold regions (Hepting 1971).

## Root and Butt Rots

*Phellinus (Poria) weirii* (Murr.) Gilbertson is the principal root- and butt-rot fungus infecting western redcedar (Hepting 1971). Redcedars and Douglas-firs are the most frequent hosts of *P. weirii* (Smith 1978). The *P. weirii* hosted by western redcedar seems to be different from that hosted by Douglas-fir and other northwestern conifers, however. *P. weirii* sporophores are perennial on western redcedar, annual on other conifers (Buckland et al. 1954). Furthermore, nonredcedar isolates are less able to parasitize western redcedar than isolates from the redcedar race (Morrison 1969). Ectotrophic mycelia are nearly absent on redcedar roots infected with *P. weirii* (Wallis 1976), and western redcedar is quite resistant to the fungus (Wallis 1962, Wallis and Reynolds 1967). In northern Idaho, the resulting decay usually is restricted to the first log (Canfield 1969). *P. weirii* is most damaging in the interior, attacking living trees only to a limited extent on the coast (Buckland 1946).

The shoestring root and butt rot, *Armillaria mellea* Vahl., attacks most conifer species in the Western United States (Scharpf 1978), but it is less damaging to western redcedar than to other species in the western white pine type (Hepting 1971). Nevertheless, nearly half the redcedar trees released in an Idaho thinning study were infested with *A. mellea* (Intermountain Forest and Range Experiment Station 1962, Koenigs 1969). Canfield (1969) found *A. mellea* in 15 percent of the Idaho redcedars he sampled in old-growth stands but judged the resulting decay to be insignificant in merchantable wood. Some *A. mellea* occurs on western redcedars planted in New Zealand (New Zealand State Forest Service 1944).

Less common root- and butt-rot fungi hosted by western redcedar include:

*Corticum galactinum* (Fr.) Burt (Hepting 1971)

*Fomes annosus* (Fr.) Cke. (Crops Research Division, Agricultural Research Service 1960, Hepting 1971, Scharpf 1978)

*Odontia bicolor* (Alb. & Schw.) Bres. (Hepting 1971)

*Polyporus schweinitzii* Fr. (Buckland 1946, Gecow 1952, Crops Research Division, Agricultural Research Service 1960, Shaw and Harris 1960, Hepting 1971, Scharpf 1978)

*P. tomentosus* Fr. (Hepting 1971)

*Poria subacida* (Pk.) Sacc. (Buckland 1946, Shaw and Harris 1960, Hepting 1971)

*P. vaillantii* (DC. ex Fr.) Cke. (Crops Division, Agricultural Research Service 1960, Hepting 1971).

*Poria subacida* seems to be most important.

*Phytophthora cryptogea* Pethyb. & Laff. and *P. citricola* Sawada were isolated from roots of diseased western redcedars (Young and Strouts 1976). *P. cinnamomi* Rands also infects redcedar roots but does little damage (Evans 1978). Western redcedar seems to be resistant to *P. cinnamomi* (Robertson 1969) and *P. lateralis* Tuck. & J. A. Milb. (Milbrath and Young 1949).

## Stem Diseases

Western redcedar has no major stem diseases, but several minor fungi occur on weakened or dead redcedar stems:

*Aleurodiscus amorphus* (pers. ex Fr.) Rab. (Hansbrough 1934, Hepting 1971)

*A. amylaceus* Rog. & Jacks (Hepting 1971)

*A. cerussatus* (Bres.) Hoehn. & Litsch. (Hepting 1971)

*A. lividocoeruleus* (Karst.) Lemke (Hepting 1971)

*A. tsugae* Yas. (Hepting 1971)

*A. weirii* Burt (Hepting 1971)

*Chloroscypha seaveri* (Hepting 1971)

*Coryneum cardinale* Wagen. (Grasso 1952, Sutton and Gibson 1972, Strouts 1973)

*Cucurbidothis conjuncta* Petr. (Hepting 1971)

*Diaporthe lokoyae* Funk (Funk 1973)

*Hendersonia thyoides* Cke. & Ell. (Hepting 1971)

*Pestalotia funerea* Desm. (Hepting 1971)

*Valsa abietis* Fr. (Hepting 1971)

*V. kunzei* Fr. (Hepting 1971)

*V. weiriana* Petr. (Hepting 1971)

Redcedar seems to be resistant to the cypress canker caused by *Monochaetia unicornis* (Cke. & Ell.) Sacc. (Fuller and Newhook 1954) but susceptible to the crown gall caused by *Agrobacterium tumefaciens* (E. F. Smith & Town.) Conn. (Hepting 1971).

## Trunk Rots

Buckland's (1946) investigations of decay in British Columbia western redcedar constitute the best general assessment of redcedar trunk rots. He ranked the major fungi in order of importance, with the most damaging listed first:

Coastal British Columbia

*Poria asiatica* (Pil.) Overh.
*Poria albipellucida* Baxt.
*Fomes pini* (Thore) Lloyd
*Merulius* sp.
*Poria subacida*

Interior British Columbia

*Poria asiatica*
*Phellinus weirii*
*Fomes pini*
*Polyporus balsameus* Pk.
*Merulius* sp.
*Poria subacida*

Other fungi that attack the heartwood of living redcedar stems less extensively were also identified by Buckland:

*Coniophora cerebella* (Pers.) Pers.
*Fomes nigrolimitatus* (Rom.) Egeland
*F. pinicola* (Swartz ex Fr.) Cke.
*Omphalia campanella* (Batsch. ex Fr.) Quél.

He found the major fungi decaying redcedar sapwood and slash to be *Polyporus cuneatus* (Murr.) Zell. and *Hymenochaete tabacina* ([Sow.] Fr.) Lév.

Kimmey (1956) found that *Poria albipellucida* accounted for about 45 percent of the western redcedar trunk rot in southeastern Alaska. *Phellinus weirii* accounted for about 41 percent, and *Poria ferrugineofusca* Karst. was responsible for 3 percent. Kimmey found no sporophores on living redcedar trees in Alaska, so he used sucker limbs, trunk scars, dead sections, and rotten burls as decay indicators. Similar indicators were used by Canfield (1969), but Canfield found some fungal sporophores in northern Idaho. *Phellinus weirii* and *Polyporus sericeomollis* Rom. were the most common redcedar decay fungi identified by Canfield. He encountered slightly more decay where the fern *Gymnocarpium dryopteris* was present than where it was absent.

Isenberg (1951) rated *Phellinus weirii* as the most serious western redcedar decay, with *Polyporus anceps* Pk. and *Fomes pini* important on old trees. *P. sulphureus* Bull. ex Fr. damages redcedar trees in Washington (Shaw and Harris 1960), and *Echinodontium tinctorium* (E. & E.) E. & E. is occasionally found on western redcedars in British Columbia (Etheridge 1972). Young redcedar trees seem quite resistant to *Fomes annosus* (Fr.) Cke. in England and Poland (see Kosturkiewicz and Meixner 1956, Greig 1974, Forestry Commission, London 1978).

Nelson (1976) found western redcedar heartwood resistant to colonization by *Phellinus weirii*. Similar work with *Lenzites trabea* Pers. ex Fr. (Morton and French 1966) and decay tests with *L. trabea, Fomes subroseus* (Weir) Overh., *Lentinus lepideus* Fr., *Merulius lacrymans* (Wulf.) Fr., and *Coniophora puteana* (Schum. ex Fr.) Karst. (Scheffer 1957, Jacquiot and Lapetite 1960, Lutomski and Raczkowski 1963) have shown most redcedar heartwood to be resistant to most decay fungi. Resistance to *Poria incrassata* (B. & C.) Burt and *P. monticola* Murr. is variable, however (Scheffer 1957), and dark-colored inner heartwood is less resistant to decay than light-colored outer heartwood (see Findlay and Pettifor 1941, van der Kamp 1975).

Dead western redcedar trunks were slowly decayed by *Polyporus cuneatus* (Murr.) Zell. (14.4 percent of the decay), *P. versicolor* L. ex Fr. (2.8 percent), and *Fomes applanatus* (Pers. ex S. F. Gray) Gill (0.7 percent) after being windthrown on the Olympic Peninsula (see Boyce 1929, Buchanan 1940). The decay probably occurred in sapwood. Eslyn and Highley (1976) found western redcedar sapwood resistant to soft-rot attack, moderately resistant to white-rot attack, and susceptible to brown-rot attack.

## Product Decay

Several fungi were associated with brown sap rot of western redcedar poles in northern Idaho (Southham and Ehrlich 1950):

*Polyporus guttulatus* Peck
*Coniophora puteana*
*C. arida* (Fr.) Karst.
*C. olivacea* (Fr.) Karst.
*C. olivascens* (B. & C.) Massee
*Paxillus panuoides* Fr.
*Poria vaillantii* (DC. ex Fr.) Cke.
*Merulius pinastri* (Fr.) Burt.

*Polyporus guttulatus* was most important in Idaho. Elsewhere, *Lenzites trabea* Pers. ex Fr. is important (Eslyn 1970). Tests of decay resistance showed the lower and middle thirds of redcedar poles to be more resistant than the upper third (Englerth and Scheffer 1954).

## Extractives and Decay

Heartwood color is associated with extractive content and decay resistance. Dark-colored heartwood near the center of a redcedar tree is low in both thujaplicins and resistance; light-colored heartwood near the periphery is high in both (van der Kamp 1975). The thujaplicins are highly toxic to a great variety of wood-destroying fungi (Erdtman and Gripenberg 1948b, Roff and Atkinson 1954, Roff and Whittaker 1959, Rudman 1962, Freydl 1963). Indeed, thujaplicins are about as active as pentachlorophenol (Rennerfelt 1948) — concentrations of 0.001-0.002 percent inhibit fungus growth (Rennerfelt and Nacht 1955). They apparently inhibit oxidative phosphorylation in the affected fungi (Lyr 1961). Many fungi may have the ability to chemically change nearby thujaplicin extractives to nontoxic material, however, thus becoming able to overcome increasingly high concentrations of the toxic heartwood extracts (Southam and Ehrlich 1943). This may explain the great amount of heart rot in mature western redcedar — heart rot that progresses outward from the center of the tree and is associated with reduced thujaplicin concentrations in the older, central heartwood.

## Birds and Mammals

Western redcedar seeds may be sown safely (McKeever 1942), for ground-feeding birds and small mammals prefer Douglas-fir and western hemlock to redcedar seeds in western Oregon (see Gashwiler 1967). Pregermination rodent damage is minor (Helmers 1946, Boyd 1959). Redcedar mortality is high between the beginning and end of germination, however (Gashwiler 1970), so birds and small mammals may be important during the germination period.

Redcedar seedlings and saplings are browsed by deer and elk. They constitute one of the most important conifer foods of black-tailed deer in the coastal forest region of southern Vancouver Island (Cowan 1945). Redcedar was more severely browsed than Douglas-fir, western hemlock, or Pacific silver fir on the Olympic Peninsula (Gockerell 1966). All small western redcedars in the lower cedar groves of the Selway-Bitterroot wilderness in Idaho may have been destroyed by wintering deer and elk (Habeck 1978). Redcedar is a major winter food for big game in the northern Rocky Mountains. Deer browse redcedars all year long in British Columbia, and elk feed on them during the fall, winter, and spring (see Packee 1975). Introduced Sitka blacktail deer have greatly reduced redcedar regeneration in large portions of the Queen Charlotte Islands.

Black bears remove redcedar bark and feed on the exposed sapwood in western Washington (Radwan 1969). Opossums limit western redcedar growth in Westland, New Zealand (Weston 1971).

Domestic animals also damage young western redcedars. Cattle browsed redcedar in preference to Douglas-fir in northwestern Oregon (see Howell 1948), and sheep damaged redcedar reproduction more than that of other trees in northern Idaho (Tisdale 1961).

## Genetics

Redcedar seed orchards have been established in Denmark (Søegaard 1956b), where resistance to the leaf blight caused by *Didymascella thujina* has been shown to be homozygously recessive (Søegaard 1956a, 1966, 1969). Søegaard's investigations indicate that frost resistance in western redcedar is inherited in the same way as leaf-blight resistance. Both seem to vary with stage of physiological development, but the redcedar clones most damaged by leaf blight are also most damaged by frost (see Larsen 1953).

Tests of several seed sources in North America showed wide variations in frost hardiness. Trees grown from inland sources were hardier than those from coastal areas (Boyd 1959, Sakai 1972, Sakai and Weiser 1973). No significant difference in leaf-oil terpene composition was found between inland and coastal populations by Von Rudloff and Lapp (1979), however, who observed that western redcedar has one of the lowest degrees of variability found thus far in northern North American conifer species. Copes (1981) detected no isoenzyme variation among widely separated western redcedar populations in Oregon and Washington, suggesting that management of redcedar by cultural procedures may yield greater returns than genetic improvement programs. Nevertheless, plantation trials indicate that Alaska redcedar provenances are inferior to those from Oregon and Idaho when grown in Poland (Ilmurzyński et al. 1968).

Western redcedar is well suited for the use of haploidy in tree breeding (Winton and Stettler 1974). Von Pohlheim (1970, 1971, 1972, 1977a, 1977b) studied somatic mutations and chimeras in haploid and triploid cultivars.

## Horticulture

Western redcedar is often cultivated as an ornamental tree in Europe (Sargent 1933). It is an excellent hedge shrub, standing trimming well and rarely spreading too far (Edlin 1968). Redcedar hedges planted along roadsides in Switzerland deflected and partially filtered traffic-polluted air, reducing lead contamination at offroad locations (Keller 1974).

At least three horticultural varieties of western redcedar are grown in North America (Rehder 1940). *Thuja plicata* var. *atrovirens* Sudw. has dark green leaves. The *fastigiata* Schneid. variety has columnar form, and variety *pendula* Schneid. has slender, pendulous branches. In addition, a haploid variety — *gracilis* Beissn. — has been studied in Germany. Von Pohlheim (1972) found this haploid variety less tolerant of irradiation and more subject to irradiation-induced mutation than the normal diploid. He selected a mutant form with pendent, filiform branches (von Pohlheim 1977a) and studied diploidization in the periclinal chimeric shoot apices of variety *gracilis* (von Pohlheim 1971, 1977b). Simak et al. (1974) examined male strobilus development and microsporogenesis in this haploid variety. *Thuja plicata excelsa* Timm. is a triploid cultivar with thicker and darker leaves than *T. plicata* (von Pohlheim 1970).

# Physiology and Ecology

## Meteorological Influences

**Temperature. —** Western redcedar occupies a moderate position on the temperature gradient described by Zobel et al. (1976) for the central western Cascades of Oregon. It has as few as 75 frost-free days in some portions of interior British Columbia, at least 120 to 150 frost-free days along the coast (see Krajina 1969), where the average frost-free period is commonly over 200 days (Packee 1976). Absolute minimum temperatures experienced by redcedar in British Columbia are −10° to −30°C (14° to −22°F) in coastal populations, −14° to −47°C (7° to −53°F) in the interior (Krajina 1969). Western redcedar is not very frost resistant, however; early and late frosts cause damage. Bottomland frost pockets in northern Idaho are commonly occupied by subalpine fir rather than western redcedar (Daubenmire and Daubenmire 1968).

An April frost of −9°C (16°F) that followed a mild winter destroyed almost all the young western redcedars in a Scottish plantation in 1945 (Hunter Blair 1946). An earlier April frost in England was less damaging to western redcedar than to Douglas-fir or Sitka spruce, however, and Day (1928) concluded that redcedar was more frost resistant than the other two species. Aldhous and Low (1974) observed that redcedar was also more resistant than grand fir or western hemlock to late spring frosts in Britain.

Autumn frost damage seems to vary with location and preceding weather. An unusual September frost in Ireland damaged Douglas-fir, Sitka spruce, and Scotch pine more than western redcedar in 1972 (Mooney 1973). In contrast, a November frost in Washington was more injurious to redcedar than to Douglas-fir (Duffield 1956, Daubenmire 1957) or Sitka spruce (Duffield 1956). Sitka spruce seems more resistant than redcedar to winter cold (see Phillips 1965). Nevertheless, western redcedars withstand cold winters very well in Europe (see Gecow 1952, Degen 1965, Hesmer and Gunther 1968). When bright sunny days follow a period of below-freezing temperatures, young redcedar branches and leaders often die in their native habitats (Miller 1978). Dormant twigs from the interior were much hardier than those from the coast when subjected to subfreezing temperatures in a laboratory (Sakai and Weiser 1973).

Western redcedar is susceptible to heat girdling (Haig 1936). It appears to be less tolerant of high soil-surface temperatures than Engelmann spruce, grand fir, or Douglas-fir (Larsen 1940). The exposed surfaces of upper foliage in young redcedar seedlings often "sunburn" severely, but lower, unexposed surfaces remain green (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia).

**Moisture. —** Water content in 2-year-old western redcedar seedlings was higher than in Douglas-fir or western hemlock seedlings when all three species were grown in a greenhouse by Jablanczy (1964), but western redcedar leaves lose water rapidly when severed from the parent tree (Parker 1951). The leaves are not protected from excessive transpiration by cutin and wax, and they showed no drought resistance in the physiological and anatomical investigations conducted by Oppenheimer (1967).

Redcedar is abundant in many forested swamps. It is sometimes found on sites that are too dry for western hemlock, however — in Montana (Habeck 1968, Pfister et al. 1977), Washington and Oregon (Franklin and Dyrness 1973), British Columbia (Packee 1976), and Idaho (Daubenmire and Daubenmire 1968). Daubenmire (1966) placed western redcedar between western hemlock (cooler and wetter) and western white pine (warmer and drier) in the species series that he constructed along environmental gradients in eastern Washington and northern Idaho. Redcedar dominates wet ravines and poorly drained depressions in both Glacier National Park, Montana, and the Selway Bitterroot Wilderness, Idaho (Habeck 1968, 1978), but it is almost absent where frequent flooding occurs in Glacier Park (Kessell 1979). Adequate soil moisture during the growing season seems to be essential for redcedar growth in Italy (Sanesi and Sulli 1973).

The generally observed superiority of western redcedar over western hemlock on dry sites seems to be the result of better redcedar root penetration (Haig 1936). Root penetration probably is not responsible for western redcedar superiority on wet sites, where it often is the dominant tree (fig. 3). Native redcedars are able to tolerate stagnant water tables in winter that average less than 15 cm (6 in) below the soil surface on the Olympic Peninsula (Minore and Smith 1971). Day (1957) found redcedars to be the characteristic dominants on water-retentive or wet soils in the Queen Charlotte Islands. Western redcedar seedlings tolerated year-round water table depths of only 7.5 cm (2.9 in) and 8 weeks of summer flooding in controlled experiments (Minore 1968, 1970).

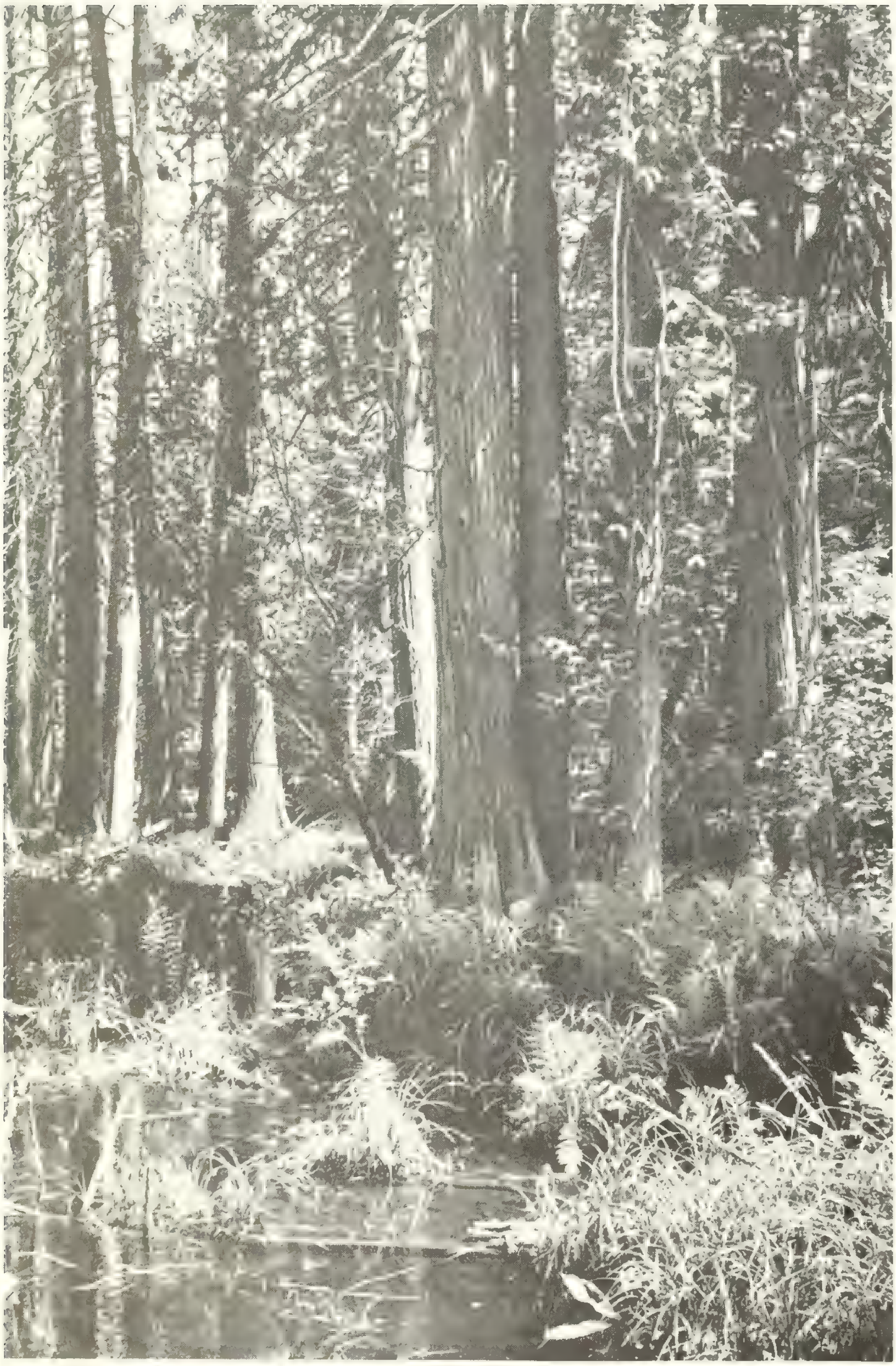

Figure 3.—Western redcedars growing on a wet site in the Washington Cascades.

**Photoperiod.** — Vaartaja (1957a) observed no significant response when he exposed 1-month-old seedlings to a single 10-hour dark period and to two 5-hour dark periods in each 24-hour day. Growth of the redcedars measured by Malcolm and Caldwell (1971), though erratic, indicated a critical day length of about 15 hours for the faster rates of growth. Western redcedar responds rapidly to increases in photoperiod, breaking dormancy faster than western hemlock or Douglas-fir (Jablanczy 1964).

**Wind.** — Western redcedar is windfirm on dry sites, where Gratkowski (1956) rated it more windfirm than Douglas-fir, western hemlock, or Pacific silver fir. Boyce (1929) also classed redcedar with Douglas-fir as resistant to windfall. Western redcedar is fairly resistant to storm damage in Germany (Volk 1968) and stands up well to wind in Britain (Streets 1962). It is not windfirm on the wet sites characterized by *Adiantum, Lysichitum,* and *Athyrium* in British Columbia (Packee 1976).

**Air pollution.** — Western redcedar is sensitive to atmospheric pollution in Britain (Streets 1962). In Germany's industrialized Ruhr area, however, it seems more tolerant of industrial fumes than Douglas-fir or western hemlock (Glocker and Krüssman 1957). German tests showed little damage to western redcedar leaves after 57 hours exposure to 2.0 parts per million (p/m) sulfur dioxide (Enderlein and Vogl 1966). Longer exposures may be more damaging; only grand fir and subalpine fir were more susceptible than redcedar when 12 conifers were tested for damage from sulfur dioxide smelter fumes in British Columbia (Scheffer and Hedgcock 1955).

Western redcedar is less tolerant of ocean spray than Sitka spruce along the west coast of Vancouver Island, British Columbia (Cordes 1973). Redcedar also is intolerant of salt-laden winds in Southland, New Zealand. In Westland, which has more rainfall, the salt damage is less serious (Weston 1971).

Clay dust from a brick works in British Columbia produced a columnar form in nearby western redcedars that led Glendenning (1948) to describe a new horticultural variety. When this columnar variety was grown in the absence of clay dust, however, it reverted to normal redcedar form (Rhodes 1955).

The aromatic compounds produced by western redcedar can influence other plants. The germination of oats, wheat, and corn was retarded or inhibited by air that had been in contact with redcedar wood (Weintraub and Price 1948).

## Fire

Western redcedar is very susceptible to fire injury (Lutz 1972). The shallow roots under a duff layer are often scorched when that duff layer burns (Flint 1925), and even surface fires may kill coastal western redcedar (McMinn 1960). Most low-site areas have fire-killed redcedar trees in southeastern Alaska, where western redcedar is very flammable (Gregory 1957). Relative fire resistance of species does not appear to be the same in coastal and inland forests, however (Minore 1979). In the Rocky Mountains, redcedar is more resistant to fire than Engelmann spruce and western hemlock, less resistant than Douglas-fir and ponderosa pine (Haig et al. 1941). Old redcedar trees commonly are fire scarred in northern Idaho (Daubenmire and Daubenmire 1968).

Fire-killed western redcedar timber shows little deterioration after 5 years (Wallis et al. 1974). Even the bark usually remains intact on dead trees for 5 years (Embrey 1963). Fire killing produces no immediate reduction in strength of western redcedar poles (Research News, Ottawa 1962c), and some large redcedar trees remain salvageable for almost 100 years after being killed by fire (see Smith et al. 1961b).

## Soils

**Physical properties. —** Western redcedar seems able to tolerate a wide range of physical properties in soil in most localities. It is found on all landforms, soil textures, and parent materials on Vancouver Island (Packee 1976). Coarse sandy soils are not well suited to establishment and growth of redcedar in northern Idaho and northeastern Washington, however — they are too droughty and unstable (Helmers 1946). In contrast, rocky slopes with limited soil development support western redcedar in southeastern Alaska (Gregory 1957). The wet soils developed from muskegs also are dominated by western redcedar south of Petersburg, Alaska (Stephens et al. 1970). It grows over loams, clays, sands, and chalk downland in England (Hubbard 1950, Streets 1962, Edlin 1968). Redcedar also grows on *Molina-Juncus* peat there (Zehetmayr 1954).

Forristall and Gessel (1955) concluded that western redcedar roots could grow in higher bulk densities of soil than could roots of red alder, Douglas-fir, or western hemlock. Unfortunately, they compared species growing separately on soils of differing textures. Minore et al. (1969) used a soil of uniform texture in the greenhouse and found that western redcedar roots could not penetrate the compacted soil columns penetrated by Douglas-fir, red alder, lodgepole pine, and Pacific silver fir.

Forest floors under western redcedar and Sitka spruce tend to be thicker and have higher water-holding capacities than those under Douglas-fir and western hemlock in western Washington (Flannery 1940).

**Chemical properties. —** Total amounts of essential plant nutrients stored in the forest floor were greater under western redcedar and Sitka spruce than they were under Douglas-fir and western hemlock in the stands sampled by Flannery (1940) in western Washington. The data of Tarrant et al. (1951) and Daubenmire (1953) indicate that western redcedar litter is low in nitrogen and phosphorus, so Flannery's figures may have resulted from greater thickness rather than higher concentrations. Alban (1969) measured more exchangeable calcium, higher cation-exchange capacity, and higher base saturation in soils under redcedar than under western hemlock, however, and he found soil pH to be higher under the redcedar. Ovington and Madgwick (1957) found pH higher in soil under redcedar than under European beech, European larch, Sitka spruce, oaks, Norway spruce, Scotch pine, Japanese larch, Austrian pine, birch, grand fir, noble fir, Douglas-fir, lodgepole pine, western hemlock, and tamarack. Western redcedar seems to benefit the soil. It is one of the few species that can be grown on chalk downland in southern England (Aldhous and Low 1974).

Krajina (1969) observed that redcedar growth seems to be benefited by nitrification, and he associated the presence of *Sambucus racemosa* L., *Tiarella trifoliata* L., *Tellima grandiflorum* (Pursh) Dougl., *Tolmiea menziesii* (Pursh) T. & G., and *Urtica dioica* L. with favorable soil conditions.

## Nutrients and Nutrition

The nutrient contents of western redcedar foliage vary with season and site. Nevertheless, relatively high concentrations of calcium and low concentrations of nitrogen are nearly always present (see Gessel et al. 1951, Tarrant et al. 1951, Daubenmire 1953, Ovington 1956, Beaton et al. 1965, Webber 1973). Phosphorus concentrations are usually low, but Smith et al. (1968) found them to be higher in western redcedar than in Douglas-fir or western hemlock. Less sulfur was found in redcedar foliage than in the foliage of other British Columbia conifers sampled by Beaton et al. (1965).

Foliage-nutrient concentrations should be used with caution when comparing species, for relative nutrient concentrations do not always reflect relative nutrient requirements. Optimum nutrition of western redcedar may require very high nutrient levels (Krajina 1969). Redcedar seedlings apparently require more nitrogen than seedlings of Sitka spruce, western hemlock, or Douglas-fir for best growth (Krajina 1959), but redcedar can survive on poor sites (Gregory 1957). Redcedar may respond to nitrogen additions by increasing root growth in comparison with shoot growth (Smith et al. 1968). Although nitrate nitrogen seems to be used more efficiently than ammonium nitrogen in sand and solution cultures (see Krajina 1971, Krajina et al. 1973), additional work is needed to relate soil nitrate and ammonium to redcedar growth in nature. Nitrogen deficiencies result in yellowish foliage, reddish seedling stems, and foliage nitrogen concentrations less than 1.5 percent (Walker et al. 1955).

Phosphorus deficiencies result in reddish or purplish stems and older foliage (Walker et al. 1955). Although phosphorus and nitrogen deficiencies were blamed for plantation check in the upland heaths of Britain (Forestry Abstracts 1964), and phosphorus additions benefited root growth of western redcedar on sod-peat bog in Ireland (Carey and Barry 1975), redcedar is more tolerant of low phosphorus levels than Douglas-fir and Sitka spruce (Krajina 1969).

Potassium deficiencies do not seem as critical as deficiencies of nitrogen or phosphorus for western redcedar growth (see Walker et al. 1955). Walker et al. measured little decrease in seedling growth under potassium-deficient conditions but noted limber stems and drooping foliage on the affected seedlings.

Seedlings affected by calcium deficiencies show browning and dying at the tips of leader and branch shoots (Walker et al. 1955). Western redcedar may be less tolerant than western hemlock, Sitka spruce, or Douglas-fir to low levels of calcium, magnesium, or both (Krajina 1959, 1969).

Only low levels of sulfur seem to be required by western redcedar. Indeed, sulfur fertilization often caused reduced height growth of the western redcedars treated by Smith et al. (1968). This response may have been the result of pH changes induced by the fertilization, however, for western redcedar is reputed to grow best on neutral to slightly acid sites (University of British Columbia Forest Club 1959). Where sulfur deficiencies do occur, young redcedar foliage becomes yellowish and older foliage is paler than normal (Walker et al. 1955).

Western redcedar seedlings survive in the absence of boron, but they develop a variety of deficiency symptoms: Stem elongation is much restricted, and needles are closely bunched (Walker et al. 1955); branches become straplike or club shaped (Blaser et al. 1967); and stems are weak.

Comparisons of western redcedar foliage-nutrient concentrations, growth responses, and site conditions are sometimes confusing. Much of this confusion may result from a failure to distinguish between responses to low nutrient levels and responses to optimal nutrient levels. Western redcedar seems able to survive and grow in low-nutrient conditions, and it probably occurs in such conditions over much of its natural range. When supplied with abundant nutrients and moisture, however, redcedar may respond more vigorously than other conifer species. For example, western redcedar seedlings outgrew seedlings of Douglas-fir, grand fir, Sitka spruce, western hemlock, and ponderosa pine when all were grown for 2 years in raised, well-watered soil beds fertilized with nitrogen, phosphorus, and potassium.[8]

## Asexual Reproduction

Three types of asexual reproduction of western redcedar occur in nature: layering (Schmidt 1955; Habeck 1968, 1978), rooting of fallen branches, and branch development on fallen trees. The resulting "veglings" were more abundant than seedlings in mature stands sampled by Parker (1979) in northern Idaho. Much of the redcedar regeneration observed by Dyrness et al. (1974) in the western Cascades of Oregon consisted of individuals developed from branches of saplings that were knocked down and have since rooted.

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[8] Paper, "Growth of forest tree seedlings in sewage sludge amended media," by R.J. Zasoski and C.S. Bledsoe. 1980. Presented at the 53d annual meeting, Northwest Scientific Association, in Moscow, Idaho. Abstract on file, Forestry Sciences Laboratory, Corvallis, Oregon.

Redcedar clones are easily propagated by rooting stem cuttings (Larsen 1953). Untreated cuttings will root, and Søegaard (1956a) achieved 50 to 80 percent success by using new shoots cut in July and August. Nevertheless, treatment with growth-regulating substances improves results. Verleyen (1948) found $\alpha$-napthalene acetic acid more effective than $\beta$-indole-acetic acid in early rooting trials. Indole-butyric acid (I.B.A.) improves rooting speed, the number of cuttings rooted, and the total length of roots per cutting (Matthews 1951). The best I.B.A. concentrations are 3,000 p/m for a 1-minute dip and 200 to 400 p/m for a 4-hour soak (Kalmár 1973). When a talc carrier is used, 6.25 p/m is effective (Matthews 1951).

Coleman and Thorpe (1977) successfully grew western redcedar plantlets from both juvenile and mature tissues by applying distinct sequential treatments for the following developmental stages: meristemoid induction and adventitious bud determination; bud growth; and rooting of the resulting adventitious shoots and reestablishment in soil. Compositions of the nutrient media used in stem tissue cultures are listed by Harvey and Grasham (1969) and Coleman and Thorpe (1977).

### Sexual Reproduction

Sexual reproduction probably is more important than asexual reproduction in open clearcut units and other disturbed areas (see Parker 1979). When grown in the open, western redcedar trees begin to produce strobili at 10 years of age and usually continue every other year thereafter (Søegaard 1956a), but large seed drops occur only every 3 to 4 years (Schopmeyer 1974).

Strobilus formation is induced by branch-girdling in western redcedar (Forestry Commission, London 1970; Longman 1976). Treatment with gibberellins also induces strobilus formation (Coutts and Bowen 1973, Longman 1976). Indeed, staminate strobili can be induced in 7- to 9-month-old redcedar seedlings by applying foliar sprays of gibberellin $A_3$ under long-day conditions (Pharis and Morf 1967). Long days were used by Coleman and Thorpe (1978) to induce staminate strobilus formation in western redcedar shoot tips cultured on nutrient media in the presence of high gibberellin concentrations. Simak et al. (1974) also used long days and gibberellin to induce staminate strobili in redcedar cuttings. A short photoperiod, cold treatment, or both must be applied if strobili are to develop further, however (Pharis et al. 1969, Pharis and Morf 1972). Pharis and his coworkers combined the gibberellin treatment with a sequence of long day, short day, long day to produce both staminate and ovulate strobili on young redcedar seedlings. They found that cold temperatures during the short-day treatment increased the number of developing strobili and that cold alone was effective, regardless of photoperiod.

Under natural conditions on Vancouver Island, staminate strobili are initiated during the long days of early June, and ovulate strobili are initiated during the long days of early July (Owens and Pharis 1971). Meiosis begins in the fall, but it is arrested at the pachytene stage from November until late January (Owens and Molder 1971). Development resumes in February near Victoria, British Columbia, where pollination occurs in early March and fertilization is accomplished in late May (Owens and Molder 1980). Pollination is delayed until late May or early June in northern Idaho (Schopmeyer 1974). Peak pollen release occurs around noon, when relative humidities are low (Haard 1971). Self-pollination is common (Søegaard 1956a). The pollination mechanism in western redcedar does not allow an accumulation of pollen, and redcedar ovules are not all receptive at the same time, so several sources of pollen shed over a prolonged period are advantageous (Owen and Molder 1980).

Western redcedar cones mature about 5 months after pollination west of the Cascades, about 3 months after pollination in northern Idaho (Schopmeyer 1974). Seedfall begins soon thereafter, continuing throughout the following winter in most locations (see Haig et al. 1941, Fowells 1965, Gashwiler 1969). Heavy seed crops are common (see Garman 1955, Schmidt 1955, Gashwiler 1969, Harris and Farr 1974).

Western redcedar seeds retain their initial viability for at least 3 years when stored at −18°C (−0.4°F) (Barton 1954, Holmes and Buszewicz 1958). Some germination occurred after 6 years when Allen (1957) stored redcedar seeds at 0°C (32°F), but −18°C (−0.4°F) seems to be a better storage temperature. Stratification may improve the germination of some dormant seed lots (Schopmeyer 1974). In others, it may lower the germination capacity (Jablanczy 1964). Schopmeyer cites a 0.2-percent solution of potassium nitrate in the germination medium as an alternative to cold stratification.

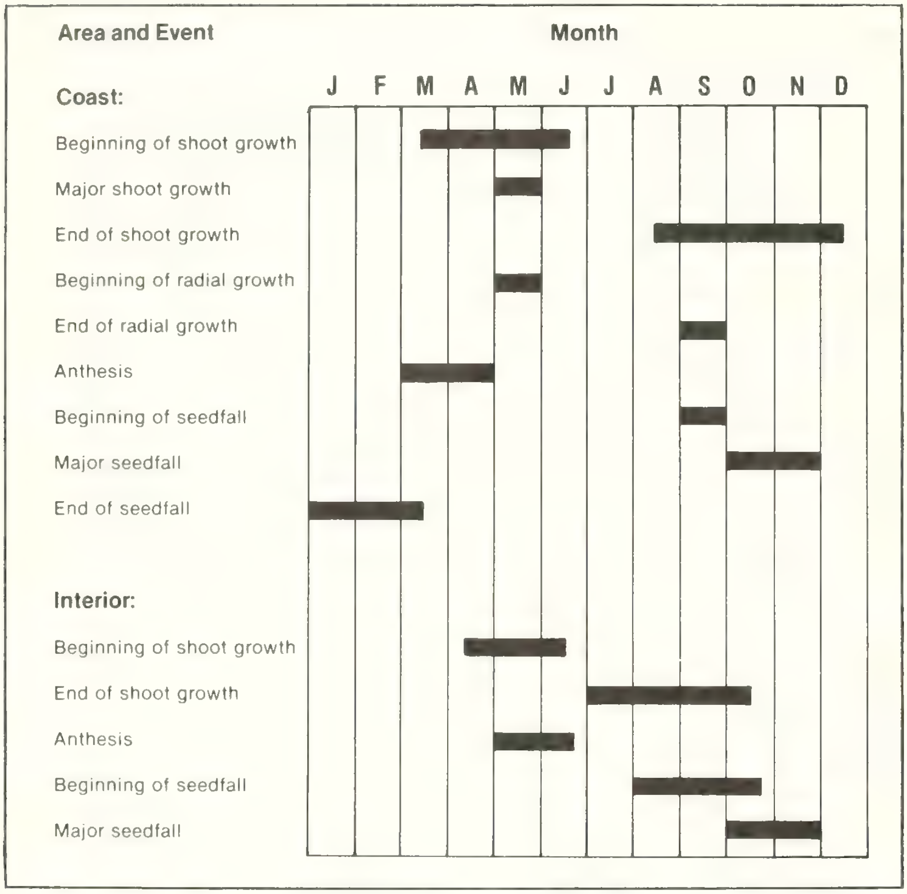

Figure 4.—Phenology of native redcedar, by area (from Haig et al. 1941, British Columbia Forest Service 1950, Garman 1955, Buckland 1956, Pacific Northwest Forest and Range Experiment Station 1957, Hedlin 1964, Hetherington 1965, Williams 1968, Owens and Pharis 1971, Schopmeyer 1974, Schmidt and Lotan 1980).

## Phenology

Phenological observations vary with year and locality. Therefore, the observations summarized in figure 4 probably were influenced by the years and locations in which they were recorded.

Phenological comparisons among species may be less influenced by seasonal and spatial variations. Western redcedar had the longest height-growth season of any conifer measured by Williams (1968) in the upper slope forests of Oregon. Walters and Soos (1963) found that leader growth commenced earlier and accelerated faster in redcedar than in Douglas-fir, western hemlock, or western white pine, but then continued at a lower rate — for a longer period — than in the other species.

Radial growth phenology is not as easy to compare. It seems to vary among species from year to year (Reukema 1965). Redcedar radial growth periods are strongly influenced by altitude in the interior (see Daubenmire 1946).

## Regeneration

Western redcedar regeneration probably is seldom limited by lack of seed. A fair seed crop on four trees produced over a million seeds in British Columbia (Garman 1951), and nine trees in a mature stand produced an average seedfall of over 2 million seeds during 3 crop years (Garman 1955). The average annual crop in the coastal forests of British Columbia usually ranges from 247,000 to 2,470,000 seeds per hectare (100,000 to 1,000,000 seeds/acre) in stands with up to 25 percent redcedar (Schmidt 1955), but pure stands may yield over 148 million seeds per hectare (60 million seeds/acre) (Sharpe 1974). In the interior, average seed crops range from 54,000 to 274,000 seeds per hectare per year (22,000 to 111,000 seeds/acre per year) (see Fowells 1965, Clark 1970).

Western redcedar seeds tend to be sound as well as numerous. In a scrub stand in Alaska, 68 to 92 percent of the 38 million seeds per hectare (15 million seeds/acre) produced in 1956 were sound (James 1959). Although he recorded great variations in size of redcedar seed crop, Gashwiler (1969) found a higher percentage of filled seeds for western redcedar than for Douglas-fir or western hemlock in west-central Oregon. Redcedar seeds fall faster and do not fly as far as the seeds of western hemlock, Sitka spruce, or Douglas-fir (see Siggins 1933).

As western redcedar seeds are usually abundant and sound, an abundance of young redcedar trees would be expected on most redcedar sites. Surprisingly, they are not present in many environments. Immature stands are uncommon in coastal British Columbia (see Packee 1976). Seedlings are either rare (Neiland 1971) or they have difficulty surviving (Gregory 1957) in southeastern Alaska. They are also rare on both well-drained undisturbed sites and cutover areas on Graham Island, British Columbia (Day 1957).

Moist redcedar sites on Graham Island regenerate if undisturbed (Day 1957), and regeneration from seed is often successful on open areas disturbed by logging, windthrow, or fire in the coastal forests of British Columbia (Schmidt 1955). Moist redcedar sites also regenerate in Montana's Glacier National Park, but the regeneration is vegetative (Habeck 1968). Western redcedar is not reproducing at all in low-elevation redcedar communities within the Selway-Bitterroot wilderness of Idaho (Habeck 1978). Habeck attributed this to high populations of wildlife and a deterioration of the moist Pacific maritime influence in Idaho. Farther north, in the interior wet belt of British Columbia, 150,000 redcedar seeds were required to produce 1,000 2- to 5-year-old seedlings in a 121.5-hectare (300-acre) clearcut unit, but natural regeneration was adequate on disturbed sites within 100.6 m (330 ft) of a seed source (Clark 1970).

The failure of redcedar regeneration on some sites and the high seeds-to-established-seedling ratio on other sites are puzzling. Failures probably are not because of seed losses. Gashwiler (1967) found that a large proportion of his redcedar seeds survived until germination, which began later and finished sooner than the germination of western hemlock seeds (Soos and Walters 1963). Almost no germination occurs after the 1st year (Isaac 1940), but enough redcedar seeds should germinate to insure success on most sites. Mortality is high during the germination period, however (see Gashwiler 1970), and seedbed quality may be critical.

Germination was greater and more uniform under sand than under grit when redcedar seeds were covered in British experiments (Forestry Commission, London, 1978). Sand was a poorer seedbed than western white pine duff in Fisher's (1935) greenhouse experiments. The artificial conditions inherent in many greenhouse experiments sometimes produce misleading results, however, and those results should be applied to field situations with geat care, if at all. In field experiments, Haig et al. (1941) found western redcedar germination to be 5 to 10 times better on mineral soil than on duff. Mineral soil also is a better seedbed than moss in southeastern Alaska, but western redcedar seedlings seem to survive better than those of other species on the moss (Godman 1953). Average field survival of germinated western redcedar seeds was slightly higher on rotten Sitka spruce wood than on rotten Douglas-fir wood, rotten hemlock wood, or duff on light and moderately shaded seedbeds in coastal Oregon (Minore 1972). Heavily shaded seedbeds were associated with the best redcedar germination in coastal British Columbia (Garman 1955), where germination occurs throughout fall and winter when temperatures are favorable (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia).

Although Soos and Walters (1963) found that unburned mineral soil favors redcedar survival more than burned mineral soil, burning after logging may favor the natural regeneration of western redcedar (British Columbia Forest Service 1948b). It probably creates more mineral soil surfaces in cutover areas. Growth of redcedar seedlings was better on burned and denuded surfaces than on organic material in northern Idaho (Larsen 1940). Seedling survival is usually best on mineral soil and poorest on rotten wood (Boyd 1959), but growth of the survivors may be best on wood; 80 percent of the dominant redcedars examined by Nystrom (1980) grew on rotten logs, but only 36 percent of the suppressed trees were on rotten wood.

Throughout the range of western redcedar, disturbance of seedbeds seems to be beneficial. Partial shade is also beneficial. Drought and high soil surface temperatures damage seedlings in full sunlight, and poor root penetration causes drought damage in full shade (Sharpe 1974). Fungi probably cause the greatest early mortality (Boyd 1959).

## Shade Tolerance

Baker (1949) listed western redcedar as very tolerant. Although Schmidt (1955) observed that redcedar did not have all the characteristics usually associated with a shade-tolerant tree, most authors seem to agree with Baker's assessment. Redcedar is slightly less tolerant than western hemlock in southeastern Alaska and the south coast region of British Columbia (Packee 1976). It is also less tolerant than Pacific silver fir in British Columbia (Krajina 1965, Packee 1976). Redcedar may be more shade tolerant than western hemlock in the interior (see Haig et al. 1941). The literature indicates that shade tolerance of western redcedar along the coast may be higher in warmer zones than it is in cool zones (Packee 1976).

## Succession

Western redcedar is often present in all stages of forest succession, and Packee (1975) listed its successional positions as pioneer, seral, and climax. Multiple attributes seem to be responsible, for redcedar invades disturbed areas as widely distributed seeds but regenerates vegetatively in undisturbed areas, tolerating competition in both situations (Kessell 1979). Nevertheless, redcedar is usually considered a climax or near-climax species (see Munger 1940, Guiguet 1953, Schmidt 1955, McLean and Holland 1958, Mueggler 1965). Idaho western white pine stands are slowly replaced by a western hemlock-redcedar climax (Watt 1960). Daubenmire and Daubenmire (1968) listed redcedar as the major climax species in their *Thuja plicata/Pachistima, Thuja plicata/Oplopanax*, and *Thuja plicata/Athyrium* habitat types in Idaho. It is a minor climax species in their *Tsuga heterophylla/Pachistima* type. Pfister et al. (1977) listed redcedar as a major climax species in Montana's *Thuja plicata/Clintonia uniflora* habitat type, a minor climax species in the *Tsuga heterophylla/Clintonia uniflora* type. Western hemlock may eventually replace western redcedar in some decadent stands of southeastern Alaska (see Gregory 1957). Redcedar will be part of the climax forest on wet sites in the *Tsuga heterophylla* zone of Oregon and Washington, but it probably does not have climax status on modal or dry sites (Franklin and Dyrness 1973).

Moisture and soil conditions strongly influence the successional status of western redcedar. It is climax on wet sites in the Lake McDonald region of Glacier National Park (Habeck 1968) and on calcium-rich seepage habitats in British Columbia (Krajina 1969). Redcedar probably is an edaphic climax species rather than a climatic climax tree. Longevity should not be ignored when considering successional status, however, and very old redcedar trees are often present in climatic climax situations.

## Growth

Radial growth is similar in western redcedar and western hemlock (Walters and Soos 1962), but most of the pseudotransverse cell divisions in redcedar cambium occur near the end of the growing season (Bannan 1951). Both species produce nonrigid leaders, but they differ in proportions of lateral and leader growth. Growth of lateral branches is less than half of leader growth in western hemlock and more than 80 percent of leader growth in western redcedar (see Buckland 1956). Growth rates of lateral and terminal shoots were similar in the young western redcedars measured by Walters and Soos (1963).

Growth is not always rapid. Suppressed redcedar trees that are 200 years old but only 7.6-cm (3-in) d.b.h. and 7.6-m (25-ft) tall are not unusual (Schmidt 1955). Ability to survive such long periods of suppression may result from the ability of western redcedar to produce new root growth in full shade (see Haig 1936). It may also be a result of frequent root grafting. Eis (1972) found that dominant trees usually supported growth of the root systems and lower boles of suppressed trees. However they survive, these suppressed trees often recover well when released.

Forest inventory data show western redcedar trees in Oregon and Washington to be smaller in diameter and shorter than Douglas-firs and hemlocks of the same age on most sites (Bolsinger 1979). This is also true on well-drained soils in the south coast region of British Columbia. On moist sites, however, the coastal redcedar often is as large or larger than its associates (Packee 1976). Packee cites annual radial increments of 1 or even 2 cm (0.4 to 0.8 in) on the best moist sites.

Day (1957) found that vigor of western redcedar declined more slowly than that of Sitka spruce or western hemlock as site conditions became poorer on the Queen Charlotte Islands of British Columbia. This slower decline in relative vigor with decreasing site quality was not evident in the measurements of young tree growth recorded by Walters et al. (1961) on the lower mainland. Indeed, the opposite trend was apparent — young western redcedars grew faster than young western hemlocks and Douglas-firs on good sites, slower on poor sites. Ages of the trees being compared probably were responsible for these differences. Although western redcedar may not attain its most rapid growth rate until it is 10 to 30 years old (Jackson and Knapp 1914), it grows taller than western hemlock or Douglas-fir during the first 5 years on good sites (see Smith and DeBell 1973). Smith and DeBell's data show that Douglas-fir overtakes western redcedar by age 10, and western hemlock overtakes redcedar by age 15.

Growth of western redcedar tends to be faster than that of Alaska-cedar, but it may be extremely slow on poor sites in southeastern Alaska (Harris and Farr 1974). Height growth may reach a maximum at an early age in southeastern Alaska (Andersen 1955b). Nearby, along the north coast of British Columbia, approximately 10 years are required to produce a 1.2-m-tall (4-ft-tall) redcedar on average sites. Diameters of 0.5 to 4.6 cm (0.2 to 1.8 in) are produced on better sites during the same 10-year period (see British Columbia Forest Service 1948b). Western redcedars in the United States may require 80 years to reach diameters of 25 to 46 cm (10 to 18 in) (Lutz 1972).

Redcedar growth rates seem to be impaired by a droughty soil-moisture regime or highly leached soils on Vancouver Island, British Columbia (McMinn 1960). Redcedar seems to grow slower than western hemlock but faster than Pacific silver fir on coastal Douglas-fir sites (see Walters and Haddock 1966).

Growth of redcedar is slow in the inland western white pine type, and redcedar often forms an understory after being outgrown by associated species (Haig et al. 1941). Even when released, it often cannot keep up with grand fir, western hemlock, and western white pine in northern Idaho (Deitschman and Pfister 1973). Slow growth during the first few years makes Rocky Mountain redcedar more susceptible to drought and insolation injury than its faster growing associates (Schopmeyer 1940, McKeever 1942). Diameter growth of Rocky Mountain redcedar, however, is less affected by high elevation than the diameter growth of ponderosa pine or Douglas-fir (Daubenmire 1955).

Western redcedar growth varies greatly with site quality in Britain. Redcedar grew taller than Douglas-fir or Sitka spruce in a 14-year-old British plantation, and a 20-year-old western redcedar plantation achieved a height of 16.8 m (55 ft) and a total volume of 2.1 m³/ha (30 ft³/acre) (MacDonald 1957). These plantations probably were on exceptionally favorable sites, however, for Aldhous and Low (1974) found that the early growth of western redcedar was slower than that of Douglas-fir and Sitka spruce on most British sites. Growth tends to accelerate slightly after about 25 years (Evans 1950). Redcedar eventually outproduces Sitka spruce on British lowland sites. It becomes increasingly more productive than Douglas-fir as British site quality improves (see Aldhous and Low 1974). Indeed, Packee's (1976) analyses of the paired-plot comparisons made by Aldhous and Low indicate that redcedar volume growth exceeds that of Douglas-fir on most British sites.

Growth of redcedar also varies with site quality elsewhere in Europe. Dominant western redcedars in France have attained average heights of 19 m (62 ft) in 39 years (Andre and Lheureux 1974). Younger western redcedars in Germany grew to an average height of 7.6 m (25 ft), with at least one tree reaching a height of 10.8 m (35 ft) in 18 years (Zimmerle and Linck 1951). Danish redcedars have reached heights of 20 to 25 m (66 to 82 ft) in 50 years (Madsen 1977). Growth in the Ukraine is slower, and the largest western redcedars there were only 22 m (72 ft) tall at age 70 (Unasylva 1950).

## Productivity

Published production data for native western redcedar are rare, but three North American studies are available. In the first, Smith and DeBell (1973) assessed the productivity of short-rotation redcedar and found it poorer than that of Douglas-fir, western hemlock, or black cottonwood. In a second study, Nokoe (1978) developed a yield curve for medium-site western redcedar at Salmo, British Columbia:

| Age | Net volume *($m^3$/ha[9])* |
|---|---|
| 40 | 70 |
| 80 | 210 |
| 115 | 350 |
| 165 | 490 |
| 270 | 595 |

His mathematical models indicate that the maximum current annual increment occurs at 82 years and the maximum mean annual increment at 130 years for a medium site. For a poor site, the ages are 133 and 210 years, respectively.

In the third study, Nystrom (1980) measured volumes of 379 to 824 m³/ha (5,418 to 11, 782 ft³/acre) in 40-to 60-year-old, pure, second-growth stands of redcedar in western Washington. Of the 939 to 3,657 redcedars per hectare (380 to 1,480 per acre) in these young stands, 297 to 642/ha (120 to 260/acre) were dominants with a mean annual height growth of 0.5 m (1.64 ft) per year.

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[9] To obtain ft³/acre, multiply m³/ha by 14.2914.

**Table 6 — Growth and yield of western redcedar in Britain[1]**

| Site and height | Cumulative volume production in normal stands | Basal area of fully stocked stands before thinning | Average age of maximum mean annual increment |
|---|---|---|---|
|  | *Cubic meters per hectare*[2] | *Square meters per hectare*[3] | *Years* |
| Poor sites: |  |  | 72 |
| Age 20 | 50 |  |  |
| Age 80 | 953 |  |  |
| Good sites: |  |  | 58 |
| Age 20 | 232 |  |  |
| Age 80 | 1838 |  |  |
| Stand height: |  |  |  |
| 10 meters | 100 |  |  |
| 12 meters |  | 49 |  |
| 20 meters | 600 | 55 |  |
| 30 meters | 1400 | 70 |  |

[1] Adapted from Hamilton and Christie (1971).
[2] Multiply by 14.2914 for cubic feet per acre.
[3] Multiply by 4.3560 for square feet per acre.

More information on productivity is available for western redcedar grown outside its natural range. A Montana provenance of redcedar planted in Austria in 1897 produced yields and stem forms comparable to those of Norway spruce grown in the same district (Rannert 1976). Redcedar equaled or exceeded the yield of Norway spruce in northwestern Germany, but it was inferior to Douglas-fir when both North American species were grown there (Hesmer and Gunther 1968). Western redcedar also produced less than Douglas-fir during a trial of species in East Germany. Nevertheless, its mean annual increment (12.5 $m^3$/ha or 178.6 $ft^3$/acre) was not far below that of Douglas-fir (13.9 $m^3$/ha or 198.6 $ft^3$/acre), and redcedar increment exceeded the mean annual increments of Norway spruce (10.8 $m^3$/ha or 154.3 $ft^3$/acre), Japanese larch (10.2 $m^3$/ha or 145.8 $ft^3$/acre), European beech (9.6 $m^3$/ha or 137.2 $ft^3$/acre), and Scotch pine (8.8 $m^3$/ha or 125.8 $ft^3$/acre) on a good site near Eberswalde (Lembcke 1970).

The mean annual increment of a 57-year-old western redcedar plantation in the Wirty State Forest of Poland was 13.0 $m^3$/ha (185.8 $ft^3$/acre). When previous thinning was included, its total yield of 939.5 $m^3$/ha (13,426.7 $ft^3$/acre) was nearly twice that for pine of the same age and site quality (see Gecow 1952). Although redcedar also matched or exceeded the production of native European species in Poland's Krynica Forests, both grand fir and Douglas-fir produced more than western redcedar there (Jaworski and Majerczyk 1975).

Western redcedar productivity in France apparently varies greatly with stand age, stand density, and the environment in which it is grown. Turpin and Pardé (1959) found that a young redcedar stand produced 13 $m^3$/ha per year (186 $ft^3$/acre per year) on the Barres Estate — more than Douglas-fir (12.3 $m^3$/ha per year or 176 $ft^3$/acre per year) and second only to western hemlock (14.8 $m^3$/ha per year or 212 $ft^3$/acre per year). In contrast, Guinier (1951) observed that an 85-year-old Douglas-fir stand on the Harcourt Estate would produce about twice as much (800 $m^3$/ha or 11,433 $ft^3$/acre) as an 80-year-old western redcedar stand (400 $m^3$/ha or 5,716 $ft^3$/acre) if both had 250 trees/ha.

Danish redcedar plantations also vary in productivity. Two plantations in eastern Denmark maintained periodic annual increments of 21 to 35 m³/ha (300 to 500 ft³/acre) until age 46. One plantation then declined to a periodic annual increment of 16 to 18 m³/ha (229 to 257 ft³/acre), but the other maintained an increment of 24 to 29 m³/ha (343 to 414 ft³/acre) until age 60 (Madsen 1977).

The forest-management tables published by Hamilton and Christie (1971) seem to be the best summary of western redcedar productivity in Britain. They show that height growth of redcedar is slower than that of Douglas-fir, western hemlock, or grand fir during the first 50 years. It is sometimes faster than that of Sitka spruce, but only on poor sites. Dominant redcedars have larger diameters than other species at any given height. The volume production shown in table 6 exceeds that of Douglas-fir, grand fir, and Sitka spruce at heights of 20 and 30 m (66 and 98 ft), but is less than that of noble fir.

Where Hamilton and Christie (1971) present yields in terms of stand age rather than stand height, their normal yield tables show that cumulative volume production on good sites is lower for redcedar than for Douglas-fir, western hemlock, Sitka spruce, or grand fir — but only until age 20. For 60- and 80-year-old stands, cumulative production of redcedar equals that of western hemlock and exceeds the cumulative production of Douglas-fir or Sitka spruce on good sites.

The average age of maximum mean annual increment is older for western redcedar than for Douglas-fir, western hemlock, Sitka spruce, or grand fir on good sites. It is younger than western hemlock on poor sites, and younger than noble fir on all sites.

An early article by Jackson and Knapp (1914) provided some site information on western redcedar in terms of "short trees," "medium trees," and "tall trees." A preliminary site-class table for mature redcedars was published 34 years later (Province of British Columbia 1948). Chambers and Wilson (1972) used total age and 100-year site-index curves in developing yield tables for conifer stands of western hemlock, Sitka spruce, and western redcedar in western Washington. Differences in the shapes of height/age curves for western hemlock and western redcedar are relatively small, but redcedars usually are shorter than hemlocks at a given age (see Smith et al. 1961a). The best available site-index curves for western redcedar appear to be the preliminary, polymorphic curves developed by Kurucz (1978) for coastal British Columbia (figs. 5 and 6).

Height-age and diameter-age relationships for British Columbia redcedars were published by the British Columbia Forest Service (1948b). For example, a 15-cm (6-in) d.b.h. redcedar that is 40 years old may be expected to attain 44.5-cm (17.5-in) d.b.h. at 100 years and 93.5-cm (36.8-in) d.b.h. at 200 years on a good site in coastal British Columbia. North coast redcedars on average sites required 18 years to reach a height of 10 feet (3 m) (British Columbia Forest Service 1948b). The height-diameter relationship determined by Brown et al. (1977) for western redcedars in Montana is:

$$\text{Height} = -15.40 + 18.80\ (\text{diameter})^{0.6039}.$$

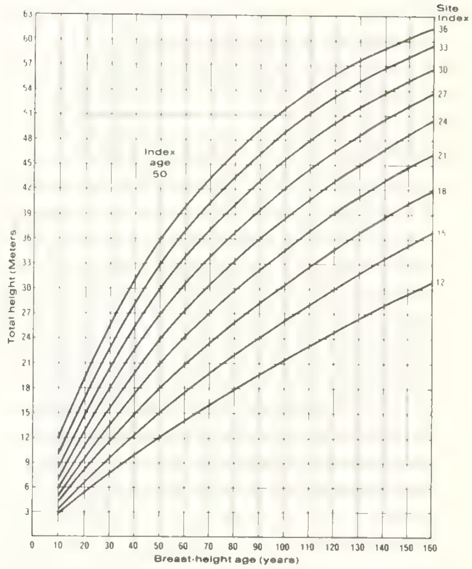

Figure 5. — Site index curves for western redcedar in coastal British Columbia (courtesy J.F. Kurucz, MacMillan Bloedel Limited).

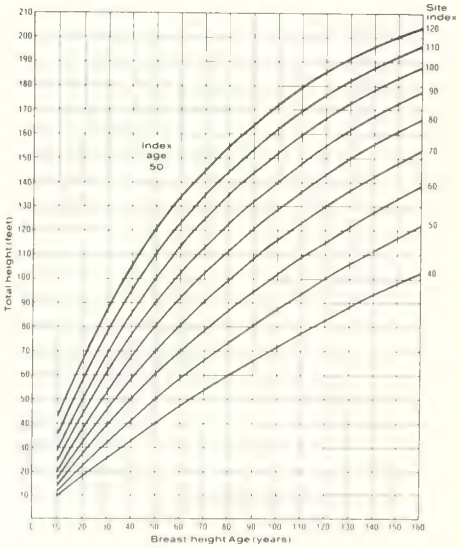

Figure 6.—Site index curves for western redcedar in coastal British Columbia (courtesy J.F. Kurucz, MacMillan Bloedel Limited).

Height growth of western redcedars in southeastern Alaska may reach its maximum at an early age, and small-diameter trees tend to have higher Girard form-classes than large-diameter trees (Andersen 1955b). Andersen's form-class measurements ranged from 55 to 76 for 9.8-m (32-ft) logs. Form-class measurements are greatly influenced by bark thickness. Bones (1962) found the average ratio of inside- to outside-bark diameters at the top of the first 4.9-m (16-ft) log of Alaska redcedar to be 0.9396. Form-class measurements have not been published as such for interior western redcedar, but butt-taper tables (Breadon 1957) are available. They permit conversion of diameters measured at 0.3, 0.5, 0.6, 0.8, 0.9, 1.1, 1.2, 1.5, 1.8, 3.0, 3.7, or 5.2 m (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, or 17.0 ft) above ground to diameter at breast height.

Western redcedar volume tables were included in Jackson and Knapp's 1914 article and in Haig's 1932 tables for the western white pine type. Several others tables have been published since. A cubic-volume table for mature western redcedar in British Columbia listed gross merchantable volume for six site classes by 2-inch (5-cm) d.b.h. intervals (Province of British Columbia 1948). The British Columbia Forest Service (1949) also published site-class volume tables. Interim tables from the Pacific Northwest Forest and Range Experiment Station (1953) were superseded by the cubic- and board-foot tables in Agriculture Handbook 92 (Johnson 1955). Those tables were based on measurements of interior western redcedar, however (table 7). The form-class volume tables published by Andersen (1955c, 1955d) for cubic- and board-foot volumes of western redcedar in southeastern Alaska are more appropriate for coastal conditions.

Constants listed by Smith and Ker (1957) for their volume equation, ($V = a + b (D^2H/100)$), included appropriate values for western redcedar in British Columbia. The British Columbia volume tables of Fligg and Breadon (1959) provided regionally applicable information by 32-foot-log position in the tree. Those of Browne (1962) included separate tables for interior and coastal redcedar in British Columbia, with the coastal volumes further segregated by mature and immature trees. Volume tables and equations for mature, old-growth redcedar were prepared by Farr and LaBau (1971) for southeastern Alaska (table 8). Immature redcedars managed for short rotations were used in deriving the volume equation published by Smith and DeBell (1973):

$$V = 0.31 + 0.234D^2H.$$

Yield data for western redcedar furnished by Jackson and Knapp (1914) for the Puget Sound area appear to be more applicable to individual redcedar trees than to stands, and relating them to modern management practices might be difficult. The preliminary redcedar growth and yield data of Smith et al. (1961b) probably would be easier to apply, because they are sorted by stand density, age, and site index. Smith et al. assumed that the growth and yield of western redcedar are generally similar to the growth and yield of western hemlock. Chambers and Wilson (1972) also seem to have made this assumption in constructing empirical yield tables for western redcedar, western hemlock, and Sitka spruce in western Washington.

**Table 7 — Volumes for western redcedar in the western white pine region**[1]

| D.b.h. | Total height of tree (feet) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 | 160 |
| *Inches* | *Cubic feet* | | | | | | | | | | | | | | | |
| 1 | 0.02 | 0.05 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 2 | .10 | .20 | 0.31 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 3 | — | .47 | .67 | 0.91 | — | — | — | — | — | — | — | — | — | — | — | — |
| 4 | — | .83 | 1.25 | 1.63 | 2.1 | 2.5 | — | — | — | — | — | — | — | — | — | — |
| 5 | — | 1.27 | 1.95 | 2.60 | 3.2 | 3.8 | — | — | — | — | — | — | — | — | — | — |
| 6 | — | — | 2.8 | 3.6 | 4.5 | 5.3 | 6 | 7 | — | — | — | — | — | — | — | — |
| 7 | — | — | 4 | 5 | 6 | 7 | 8 | 9 | — | — | — | — | — | — | — | — |
| 8 | — | — | 5 | 6 | 8 | 9 | 10 | 12 | 13 | 14 | — | — | — | — | — | — |
| 9 | — | — | 6 | 8 | 9 | 11 | 13 | 14 | 16 | 18 | — | — | — | — | — | — |
| 10 | — | — | 7 | 9 | 11 | 14 | 16 | 18 | 20 | 22 | — | — | — | — | — | — |
| 11 | — | — | — | 11 | 14 | 16 | 19 | 21 | 23 | 26 | 29 | — | — | — | — | — |
| 12 | — | — | — | 13 | 16 | 19 | 22 | 25 | 27 | 30 | 33 | 36 | 38 | — | — | — |
| 13 | — | — | — | 15 | 18 | 22 | 25 | 28 | 32 | 35 | 38 | 41 | 44 | — | — | — |
| 14 | — | — | — | — | 21 | 25 | 29 | 33 | 36 | 40 | 43 | 47 | 50 | — | — | — |
| 15 | — | — | — | — | 24 | 29 | 33 | 37 | 41 | 45 | 49 | 53 | 56 | — | — | — |
| 16 | — | — | — | — | 27 | 32 | 37 | 41 | 46 | 50 | 54 | 58 | 62 | — | — | — |
| 17 | — | — | — | — | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 64 | 69 | — | — | — |
| 18 | — | — | — | — | 33 | 39 | 45 | 50 | 55 | 60 | 65 | 70 | 76 | — | — | — |
| 19 | — | — | — | — | 36 | 43 | 49 | 55 | 61 | 66 | 71 | 77 | 83 | — | — | — |
| 20 | — | — | — | — | — | — | 53 | 60 | 66 | 72 | 78 | 84 | 90 | — | — | — |
| 21 | — | — | — | — | — | — | 58 | 65 | 72 | 78 | 84 | 91 | 98 | — | — | — |
| 22 | — | — | — | — | — | — | — | — | 77 | 84 | 91 | 98 | 106 | 114 | — | — |
| 23 | — | — | — | — | — | — | — | — | 83 | 91 | 99 | 107 | 115 | 123 | — | — |
| 24 | — | — | — | — | — | — | — | — | 90 | 98 | 106 | 115 | 123 | 131 | 139 | 146 |
| 25 | — | — | — | — | — | — | — | — | 96 | 105 | 114 | 123 | 132 | 140 | 149 | 156 |
| 26 | — | — | — | — | — | — | — | — | 103 | 113 | 122 | 131 | 140 | 149 | 158 | 167 |
| 27 | — | — | — | — | — | — | — | — | 110 | 120 | 130 | 140 | 149 | 159 | 168 | 178 |
| 28 | — | — | — | — | — | — | — | — | 117 | 128 | 138 | 148 | 158 | 168 | 178 | 188 |
| 29 | — | — | — | — | — | — | — | — | 125 | 136 | 146 | 157 | 167 | 178 | 188 | 199 |
| 30 | — | — | — | — | — | — | — | — | 132 | 143 | 154 | 165 | 176 | 187 | 198 | 209 |

[1] From Haig (1932), Johnson (1955). Volumes include stump, stem, and top.

**Table 8 — Volumes for western redcedar in southeastern Alaska**[1]

| D.b.h. | Total height of tree (feet) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 |
| *Inches* | *Cubic feet* | | | | | | | | | | | | | | |
| 6 | 2.3 | 2.7 | 3.2 | 3.6 | 4.1 | — | — | — | — | — | — | — | — | — | — |
| 8 | 4.9 | 5.7 | 6.6 | 7.4 | 8.2 | — | — | — | — | — | — | — | — | — | — |
| 10 | 8.1 | 9.4 | 10.6 | 11.9 | 13.2 | 14.4 | 15.7 | — | — | — | — | — | — | — | — |
| 12 | 11.9 | 13.7 | 15.5 | 17.3 | 19.2 | 21.0 | 22.8 | 24.6 | — | — | — | — | — | — | — |
| 14 | — | 18.8 | 21.2 | 23.7 | 26.2 | 28.7 | 31.2 | 33.7 | — | — | — | — | — | — | — |
| 16 | — | — | 27.8 | 31.1 | 34.3 | 37.5 | 40.8 | 44.0 | 47.3 | — | — | — | — | — | — |
| 18 | — | — | 35.3 | 39.4 | 43.5 | 47.6 | 51.7 | 55.8 | 59.9 | 64.0 | — | — | — | — | — |
| 20 | — | — | 43.6 | 48.6 | 53.7 | 58.8 | 63.8 | 68.9 | 74.0 | 79.0 | — | — | — | — | — |
| 22 | — | — | 52.7 | 58.9 | 65.0 | 71.1 | 77.3 | 83.4 | 89.5 | 95.7 | — | — | — | — | — |
| 24 | — | — | 62.8 | 70.1 | 77.4 | 84.7 | 92.0 | 99.3 | 107 | 114 | — | — | — | — | — |
| 26 | — | — | 73.7 | 82.3 | 90.8 | 99.4 | 108 | 117 | 125 | 134 | 142 | — | — | — | — |
| 28 | — | — | — | 95.4 | 105 | 115 | 125 | 135 | 145 | 155 | 165 | 175 | — | — | — |
| 30 | — | — | — | 110 | 121 | 132 | 144 | 155 | 167 | 178 | 189 | 201 | 212 | — | — |
| 32 | — | — | — | 125 | 138 | 151 | 164 | 177 | 190 | 202 | 215 | 228 | 241 | — | — |
| 34 | — | — | — | — | 155 | 170 | 185 | 199 | 214 | 229 | 243 | 258 | 272 | 287 | — |
| 36 | — | — | — | — | 174 | 191 | 207 | 223 | 240 | 256 | 273 | 289 | 306 | 322 | 338 |
| 38 | — | — | — | — | 194 | 212 | 231 | 249 | 267 | 286 | 304 | 322 | 340 | 359 | 377 |
| 40 | — | — | — | — | 215 | 235 | 256 | 276 | 296 | 316 | 337 | 357 | 377 | 397 | 418 |
| 42 | — | — | — | — | 237 | 259 | 282 | 304 | 326 | 349 | 371 | 393 | 416 | 438 | 461 |
| 44 | — | — | — | — | 260 | 285 | 309 | 334 | 358 | 383 | 407 | 432 | 456 | 481 | 505 |
| 46 | — | — | — | — | — | — | 338 | 365 | 392 | 418 | 445 | 472 | 499 | 526 | 552 |
| 48 | — | — | — | — | — | — | 368 | 397 | 426 | 456 | 485 | 514 | 543 | 572 | 602 |
| 50 | — | — | — | — | — | — | 399 | 431 | 463 | 494 | 526 | 558 | 589 | 621 | 653 |
| 52 | — | — | — | — | — | — | 432 | 466 | 500 | 535 | 569 | 603 | 637 | 672 | 706 |
| 54 | — | — | — | — | — | — | 466 | 503 | 540 | 577 | 614 | 650 | 687 | 724 | 761 |
| 56 | — | — | — | — | — | — | — | 541 | 580 | 620 | 660 | 700 | 739 | 779 | 819 |
| 58 | — | — | — | — | — | — | — | 580 | 623 | 665 | 708 | 750 | 793 | 836 | 878 |
| 60 | — | — | — | — | — | — | — | 621 | 666 | 712 | 757 | 803 | 849 | 894 | 940 |
| 62 | — | — | — | — | — | — | — | 663 | 711 | 670 | 809 | 858 | 906 | 955 | 1004 |
| 64 | — | — | — | — | — | — | — | 706 | 758 | 810 | 862 | 914 | 966 | 1017 | 1069 |
| 66 | — | — | — | — | — | — | — | 751 | 806 | 861 | 917 | 972 | 1027 | 1082 | 1137 |
| 68 | — | — | — | — | — | — | — | 797 | 856 | 914 | 973 | 1032 | 1090 | 1149 | 1207 |
| 70 | — | — | — | — | — | — | — | 845 | 907 | 969 | 1031 | 1093 | 1155 | 1217 | 1279 |

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[1] From Farr and LaBau (1971). Volumes are based on a 1-ft stump and 4-in-top d.i.b.

# Silviculture

## Seeding

Western redcedar regeneration occurs after clearcutting in British Columbia and Alaska (Schmidt 1955, Harris and Farr 1974). Nevertheless, natural regeneration has not been relied on to achieve immediate and complete restocking of logged areas on Vancouver Island (see Hetherington 1965). A seed and sawdust mixture was broadcast on melting snow near Cowichan Lake in an early direct-seeding trial (British Columbia Forest Service 1948a). Only 2.5 percent of the redcedar seeds survived, but 1,235 seedlings/ha (500 seedlings/acre) were alive after two growing seasons. Isaac's (1939) early work indicated probable success for broadcast seeding of western redcedar at rates of 5.4 to 10.9 kg/ha (1 to 2 lb/acre) if it were done within 2 years of slash burning. Waiting longer than 2 years on Oregon's Tillamook burn resulted in poor stocking of redcedar when the broadcast seeding was done in the spring (see Engstrom 1955).

Trials of direct redcedar seeding in northern Idaho indicated that seed spots sown in the autumn resulted in better initial stocking than those sown in the spring (Schopmeyer 1940, Helmers 1946, Schopmeyer and Helmers 1947). Protection from rodents was unnecessary when the seeds were covered with a thin layer of soil, but insufficient soil moisture, erosion, and smothering by leaves, bark, duff, and rotten wood were serious (McKeever 1942). Excellent 5th year stocking resulted when the redcedar seeds were sown on cutovers and broadcast-burned areas with stable soils and light or moderate covers of low vegetation (Helmers 1946).

## Nursery Practices

Although western redcedars amounted to only a small fraction of their total production, approximately 650,000 redcedar seedlings were produced by nurseries in Washington during 1977 (Bolsinger 1979). Redcedar has been grown in European nurseries for many years by several methods.

Redcedar seeds may be separated from the cones by kiln-drying at 32°C (90°F), shaking in a mechanical cone shaker, and fanning. They should not be dewinged (Schopmeyer 1974). Empty seeds are frequent in western redcedar cones. They may be separated from full seeds in an airstream (Schopmeyer 1974) or by immersing in petroleum ether (Lebrun 1967). Western redcedar seeds are stored at −18°C (0°F) in many western nurseries (Schopmeyer 1974).

Seedbeds should be sown in the spring for best results (see Aldhous 1967, Schopmeyer 1974). Sowing depths of 3 to 10 mm (1/8 to 3/8 in) and seedbed densities of 377 to 1,076 seedlings/m$^2$ (35 to 100 seedlings/ft$^2$) are commonly used. Half-shaded seedbeds are recommended during the first growing season (Schopmeyer 1974). Some European nurseries had better success with seedbeds of needle or leaf litter than with mineral soil (Hutt 1956, Röhrig 1958). Organic matter in the seedbed promotes the growth of *Thelephora terrestris,* however (Weir 1921), and redcedar seedlings are usually grown in soil beds. Infrequent irrigation of nursery beds ("predroughting") had no beneficial effect on western redcedar seedlings that were subsequently subjected to dry environments (see Oppenheimer 1967). Seedlings responded best to spring transplanting in Germany (Mörmann 1956).

Petroleum products have been used as nursery weedkillers. A French compound, Desherbant Carottes No. 35,[10] damaged western redcedar seedlings more than those of the firs, spruces, or pines (Bouvarel 1951). Light petroleum was less damaging to redcedar than to Douglas-fir, Norway spruce, or the larches in Denmark (Petersen 1952). Redcedar was also resistant to the winter application of propyzamide in Britain (Brown and McKenzie 1974).

Effective control of *Didymascella thujina* has been obtained by spraying cycloheximide fungicides on the affected nursery beds. The cycloheximide itself is more damaging to western redcedar than its oxime, semicarbazone, and acetate derivatives, however (Pawsey 1962a, 1965; Phillips 1962, 1964). Concentrations of 50 to 150 p/m have been recommended for these derivatives. They were most effective when applied in the spring and summer (Pawsey 1965).

Western redcedar cuttings for use in silviculture may be produced easily and cheaply (Søegaard 1956a). Søegaard recommended July and August cuttings. Untrimmed cuttings, treatment with indole-butyric acid in talc, and a sand-peat (75 percent-25 percent) rooting medium heated to 21°C (70°F) were recommended by Matthews (1951). Misting the rooting bed with a nutrient mist fortified with 45 g/100 liters (6 oz/100 gal) soluble 23-19-17 fertilizer improved cutting growth and nutrient content (Wott and Tukey 1965).

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[10] The mention of products does not imply endorsement by the U.S. Department of Agriculture to the exclusion of other products that might be suitable.

Soluble fertilizers have been added to irrigation water in the production of containerized western redcedar nursery stock. The procedures described by Owston (1974) included frequent irrigation at pH 5.0 to 5.5 in a greenhouse. Owston's redcedars were sown in mid-June in Styroblocks[11] filled with a peat-vermiculite mixture, grown all summer in the greenhouse, and hardened-off in late October to mid-November. The seedlings were ready to plant in January and February. Unfortunately, containerized western redcedar seedlings have not survived as well as bare-root stock when planted in western Oregon and western Washington (see Owston 1977). Planting has not been very successful in Idaho (Parker 1979).

Nursery stock is frequently lifted when dormant, then kept in cold storage until field sites are ready to plant in the spring. Aldhous (1964) found western redcedar to be one of the least satisfactory species tested for survival after cold storage. His results were somewhat confounded by postplanting rainfall differences, however, and Aldhous included redcedar in only one experiment.

Rapid emergence of western redcedar from dormancy may affect its survival after cold storage. In Jablanczy's (1964) experiments with responses to photoperiod, western redcedar broke dormancy in 1 week. Western hemlock took about 4 weeks, and Douglas-fir did not break dormancy until about the 7th week after the beginning of artificial illumination.

## Stand Culture and Improvement

Natural even-aged stands of western redcedar seem to be relatively rare. Redcedar grows in even-aged stands on poor sites in southeastern Alaska, however (Gregory 1957), and even-aged redcedar plantations are occasionally established. Redcedar seedlings were planted at 0.3- by 0.3-m (1- by 1-ft) spacing in the lower Fraser River Valley and studied for 15 years by Smith and DeBell (1973) to determine short-rotation yields in pure, dense stands. They were less productive than stands of Douglas-fir, western hemlock, or black cottonwood when grown this way.

The four small stands of almost pure, second-growth redcedar studied by Nystrom (1980) in western Washington were essentially even aged, and his reconstruction of their growth and development led to the following conclusions:

- Douglas-firs seem able to dominate western redcedars even if they become established 5 years later.

- Redcedars are rapidly overtopped by red alders, but they survive under an alder understory.

- On moist sites, dominant and intermediate crown classes are distinguishable by age 5 in western redcedar. Dominant and codominant classes can be identified by age 25. Stratification into crown classes occurs more slowly on dry sites.

- On moist sites where crown class differentiation occurs early, height growth of redcedar is not noticeably affected by stand density. Diameter growth varies inversely with density.

- An initial stocking level of at least 2,470 trees/ha (1,000 trees/acre) will produce more volume by age 25 than lower levels. After age 25, about 1,235 trees/ha (500 trees/acre) with not more than 490 dominants/ha (200 dominants/acre) may provide maximum volume growth.

- When grown in fully stocked, pure stands, the stem form of western redcedar is comparable to other western conifers.

Nystrom suggested the establishment of 2,470 redcedars/ha (1,000 trees/acre) on site III (McArdle et al. 1961), with a merchantable thinning to remove intermediates at age 25. The residual stand of 940 redcedar dominants and codominants per hectare (380 per acre) could be crown-thinned thereafter. The ages of first thinning recommended by Hamilton and Christie (1971) range from 21 on good sites to 30 on poor sites in Britain.

Mixed-species, uneven-aged stands with a western redcedar component are more common than pure stands. In the mixed-species stands of British Columbia, redcedar may furnish an interim pole crop that will provide financial help in carrying Douglas-fir and western hemlock to maturity (Gilmour 1945). In Idaho, well-established redcedars grow well in the understory if they have a reasonable amount of space (Watt 1960). Redcedar has been underplanted successfully in the western white pine type of Idaho (Haig 1936), in Britain (Hubbard 1950), and under Scotch pine in East Germany (see Lembcke 1970). Interplanting was successful in the Podocarp forests of New Zealand (Hocking and Mayfield 1939), where the redcedars were able to maintain their position with competing second growth and should furnish an early timber yield while the native natural regeneration is devoping to maturity (New Zealand Director of Forestry 1940). Small groups ("nests") of western redcedar and other North American species were recommended by Ilmurzyński et al. (1968) for the forests of Poland.

Several elaborate trials of larch-redcedar (Evans 1950, Jones 1964) and oak-redcedar (Keatinge 1947,

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[11] Styroblocks are rectangular pieces of styrofoam containing cavities in which tree seedlings are grown.

Jones 1964) mixtures were carried out in Britain. The larch-redcedar stands were two-storied with larch as the overstory. Western redcedar tended to form an overstory in the oak-redcedar stands, acting as a nurse crop. Jones (1964) found that British oaks grew taller than redcedars on wet ground where competition from other vegetation was extreme, creating a redcedar understory.

Western redcedar understories seem capable of responding well to release after overstory removal (Leaphart and Grismer 1974) when the overstory is of another species. When both the overstory and understory are western redcedar, translocation through root grafts to cut stumps renders thinning from below more effective than thinning from above (see Eis 1972). The largest understory redcedars and those with least overstory competition usually respond best to overstory removal in the western white pine type (Leaphart and Foiles 1972). When that overstory is removed all at once, however, the initial increase in understory growth may be followed by redcedar chlorosis and root rot 20 years later (Intermountain Forest and Range Experiment Station 1962, Koenigs 1969). Leaphart and Foiles (1972) found that gradual removal of the overstory worked better, stimulating growth of the redcedar understory without producing chlorosis or increasing root rot. Western redcedars released in Danish thinning trials had less lower stem taper and more upper stem taper than unreleased trees (Madsen 1977). Release through herbicide use is complicated by western redcedar's susceptibility to dormant sprays of 2,4-D and 2,4,5-T iso-octyl esters in diesel oil (Packee 1976).

Taper and tree form of redcedar are profoundly influenced by stand density. From 1,976 to 2,470 trees/ha (800 to 1,000 trees/acre) are needed to maintain good form and prevent "candelabra" growth of western redcedar on Vancouver Island, British Columbia (personal communication, Edmond C. Packee, MacMillan Bloedel Limited, Nanaimo, British Columbia). Unpruned western redcedars are valueless in New Zealand, but epicormic branching in open conditions makes pruning ineffective except in dense, dark stands (Weston 1971). Pruning did not cause rot or other defects in Norway, and the pruning season did not affect results (Bauger and Orlund 1962).

Fertilization with phosphorus and potassium improved western redcedar growth in Irish peat-bog plantations (Carey and Barry 1975). Small, often negative growth correlations were associated with the redcedar fertilization experiments of Smith et al. (1968) in British Columbia, however. The British Columbia fertilization had no obviously beneficial influence on production of redcedar cones.

## Harvesting

As western redcedar is seldom found in pure stands within its native range, it is usually harvested with Douglas-fir, western hemlock, and other associated species (see McBride 1959). When partially cut, mixed stands in the interior wet belt of British Columbia gave the maximum economic return when western redcedar was cut to 30-cm (12-in) d.b.h., western white pine to 41 cm (16 in), and all other species to 36 cm (14 in) in 1956 (Stewart 1956). Partial cutting is seldom used, however. Western redcedars cannot be left as scattered seed trees in coastal British Columbia, where even redcedars along clearcut margins may be lost to windthrow or exposure (Garman 1955). Most redcedars are harvested by clearcutting.

Large quantities of slash are created in clearcut harvesting operations; western redcedar leaves more slash than other northwestern species (see Olson and Arnold 1959, Gockerell 1966). Tables of residues by individual tree and basal area prepared by Snell and Brown (1980) indicate that lower weights of sound slash are produced by redcedar than by Douglas-fir, grand fir, western hemlock, or ponderosa pine, however; the large quantities of slash probably result from the large amounts of cull and breakage associated with most redcedar harvesting. Breakage can be reduced by pulling large old-growth redcedars uphill (Guimier 1980). The additional directional felling costs are recovered through increases in harvested volume and improved log quality.

When slash from decadent western redcedar-western hemlock stands was burned, a greater proportion of redcedar than of hemlock slash was consumed (Muraro 1971) — a result of greater longitudinal and horizontal fracturing of the redcedar. When fracturing is not a factor, fresh western hemlock slash is at least as flammable as western redcedar slash (see Olson 1953, Fahnestock 1960). Fire spreads slower in hemlock when the slash from both species is 1 year old (Fahnestock 1960); hemlock drops its foliage, redcedar does not. The slash of both species becomes less flammable when chipped (Fahnestock 1953). The fire hazard normally associated with cutting of redcedar poles was reduced by skidding entire pole-size trees to the landing, where the slash was chipped and blown over the edges (Olson and Arnold 1959).

Chipping slash instead of burning it certainly reduces the fire hazard, but its effect on redcedar regeneration seems uncertain, and chipping is seldom practical. Although western redcedar can establish itself readily after logging with or without slash burning (Schmidt 1955), it seems to regenerate better after burning on the northern coast of British Columbia (British Columbia Forest Service 1948b). Slash burning has little effect on species composition in the hemlock-cedar type of coastal British Columbia, however, and it may retard the successful conifer regeneration that usually occurs there (Stoodley 1925). Disturbance of the forest floor seems essential for natural redcedar regeneration (Clark 1970). Slash burning probably is not.

## Discussion

The various subjects included in this report have not been equally discussed. Relative length and detail included in each section were determined by the amount of information available, not by their importance. For example, the section on products is twice as long as the section on silviculture; this inequality seems particularly important. Western redcedar wood is a highly valued, intensively used product that has been studied in great detail. Unfortunately, much less time, money, and effort seem to have been invested in learning how to grow the wood. More information is needed on site evaluation, nursery culture, planting techniques, fertilization, optimum stand densities, thinning of redcedar, and management of mixed species. Trees with desirable annual ring widths, knot characteristics, and forms might even be grown to order if the silviculture of redcedar were truly understood.

A true understanding of silviculture rests on foundations of physiology, ecology, genetics, mensuration, and economics. Adequate knowledge about western redcedar is lacking in all five categories. For example, the relation of moisture to redcedar regeneration and growth should be further investigated. So should its growth on various sites — sites that are objectively described and defined. The breeding of superior redcedar planting stock has scarcely begun. Accurate local volume tables and yield information are scarce, as are comparative economic analyses of mixed- compared with pure-stand culture and redcedar rotation lengths.

Redcedar rotations do not seem to have been seriously considered apart from the rotations of associated species. Indeed, redcedar timber often has been managed like a valuable mineral that is mined when found in association with other minerals or reclaimed from old mine tailings (i.e., logging residues of former years). Utilization technology is advanced, but redcedar usually has been removed, refined, manufactured, and managed as a declining, nonrenewable resource.

Western redcedar is a renewable resource that need not decline. It can be renewed and used forever, as are several other tree species now being planted and managed intensively. More research on the culture of redcedar and a different management philosophy may be necessary, however. Western redcedar differs from Douglas-fir or western hemlock, and it should be managed differently — not as just another associated species, but as a major timber crop.

## Recommendations for Management

The techniques used to manage other major timber crops are often inappropriate for western redcedar, but few techniques have been developed for redcedar. Management recommendations are based on the site, regeneration, growth, yield, tolerance, and longevity information in this report. As they have not been applied in a coordinated redcedar management program, they should be considered plausible suggestions rather than guidelines.

- Western redcedar management sites should be chosen with care. Moist, fertile conditions characterized by the presence of *Athyrium filix-femina, Clintonia uniflora, Dryopteris austriaca, Gymnocarpium dryopteris,* and *Rubus parviflorus* are best.

- Redcedar probably should be grown in pure stands when sawtimber, shingles, or shakes are the desired products. Even-aged mixtures of redcedar and other conifers will be harvested either too early for the redcedar sawtimber or too late for the other conifers when mixed-species, even-aged stands are clearcut.

- Redcedar can be grown in mixed stands when poles are to be produced under even-aged management regimes.

- Redcedar is suitable for uneven-aged management, either in pure or mixed stands. Vegetative regeneration probably will be more efficient than sexual regeneration where the selection system is practiced.

- Direct seeding with redcedar is practical and effective where a mineral soil seedbed is available. Rates of 5 to 10 kg/ha (1 to 2 lb/acre) seem appropriate for broadcast seeding. The seeds should be covered with a thin layer of soil when seed spots are used. Sowing should be done in the fall.

- Where mineral soil seedbeds are
ot available, planting may be effec-
ive. Recently lifted, bare-root stock
hould be used, and cold storage
hould be avoided.

- Redcedar plantations should be
ense, with 1.2- to 1.5-m (4- to 5-ft)
pacing between seedlings.

- Where pure, even-aged stand
anagement is practiced, inter-
ediate crown classes should be
emoved in a light thinning at about
ge 30. A nearly closed canopy
hould be maintained at all times,
owever; open-grown redcedars tend
o develop poor form, excessive
imbs, and multiple tops.

- Where western redcedar is man-
ged in mixed-species or uneven-
ged stands, its shade tolerance
nd long life should be considered.
edcedars will tolerate understory
onditions in mixed-species stands.
n uneven-aged stands, they should
aintain acceptable growth rates
ver long periods. Excessive crown
pace should be avoided under all
anagement regimes.

## Acknowledgment

Michael E. Dubrasich, formerly forestry technician, searched much of the literature summarized here.

## Common and Scientific Names of Trees

| Common Name | Scientific Name |
|---|---|
| Alaska-cedar | *Chamaecyparis nootkatensis* (D. Don) Spach |
| Alpine-ash | *Eucalyptus delegatensis* R. T. Baker |
| Austrian pine | *Pinus nigra* Arnold |
| Baldcypress | *Taxodium distichum* (L.) Rich. |
| Bigleaf maple | *Acer macrophyllum* Pursh |
| Birch | *Betula* L. sp. |
| Black cottonwood | *Populus trichocarpa* T. & G. |
| Brisbane boxwood | *Tristania conferta* R. Br. |
| California-laurel | *Umbellularia californica* (Hook. & Arn.) Nutt. |
| Cascara buckthorn | *Rhamnus purshiana* DC. |
| Chinkapin | *Castanopsis chrysophylla* (Dougl.) DC. |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| Eastern redcedar | *Juniperus virginiana* L. |
| Eastern white pine | *Pinus strobus* L. |
| Engelmann spruce | *Picea engelmannii* Parry |
| European beech | *Fagus sylvatica* L. |
| European larch | *Larix decidua* Mill. |
| European white birch | *Betula alba* L. |
| Grand fir | *Abies grandis* (Dougl.) Forbes |
| Incense-cedar | *Calocedrus decurrens* (Torr.) Florin |
| Japanese larch | *Larix kaempferi* Sarg. |
| King-William-pine | *Athrotaxis selaginoides* D. Don |
| Larches | *Larix* Mill. spp. |
| Lodgepole pine | *Pinus contorta* Dougl. |
| Longleaf pine | *Pinus palustris* Mill. |
| Monterey pine | *Pinus radiata* D. Don |
| Mountain hemlock | *Tsuga mertensiana* (Bong.) Carr. |
| Noble fir | *Abies procera* Rehder |
| Northern white-cedar | *Thuja occidentalis* L. |
| Norway spruce | *Picea abies* Karst |
| Oak | *Quercus* L. sp. |
| Oregon white oak | *Quercus garryana* Dougl. |
| Pacific dogwood | *Cornus nuttallii* Aud. |
| Pacific madrone | *Arbutus menziesii* Pursh |
| Pacific silver fir | *Abies amabilis* (Dougl.) Forbes |
| Pacific yew | *Taxus brevifolia* Nutt. |
| Paper birch | *Betula papyrifera* Marsh. |
| Pine | *Pinus* L. sp. |
| Ponderosa pine | *Pinus ponderosa* Dougl. ex Laws. |
| Port-Orford-cedar | *Chamaecyparis lawsoniana* (A. Murr.) Parl. |
| Quaking aspen | *Populus tremuloides* Michx. |
| Red alder | *Alnus rubra* Bong. |
| Red oaks | *Quercus falcata* Michx. and *Q. rubra* L. |
| Red pine | *Pinus resinosa* Ait. |
| Redwood | *Sequoia sempervirens* (D. Don) Endl. |
| Scotch pine | *Pinus sylvestris* L. |
| Shore pine | *Pinus contorta* Dougl. var. *contorta* |
| Sitka spruce | *Picea sitchensis* (Bong.) Carr. |
| Southern yellow pines | *Pinus caribaea* Morelet, *P. echinata* Mill., *P. palustris* Mill., and *P. taeda* L. |
| Spruce | *Picea* A. Dietr. sp. |
| Subalpine fir | *Abies lasiocarpa* (Hook.) Nutt. |
| Sugar pine | *Pinus lambertiana* Dougl. |
| Tamarack | *Larix laricina* (Du Roi) I. Koch |
| Tanoak | *Lithocarpus densiflorus* (Hook. & Arn.) Rehd. |
| Walnut | *Juglans* L. sp. |
| Western hemlock | *Tsuga heterophylla* (Raf.) Sarg. |
| Western larch | *Larix occidentalis* Nutt. |
| Western redcedar | *Thuja plicata* Donn |
| Western white pine | *Pinus monticola* Dougl. ex D. Don |
| Whitebark pine | *Pinus albicaulis* Engelm. |
| White spruce | *Picea glauca* (Moench) Voss |

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1983. Western redcedar: A literature review. USDA For. Serv. Gen. Tech. Rep. PNW-150, 70 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

This report is a comprehensive compilation of information on western redcedar (*Thuja plicata* Donn) — its occurrence and abundance; associated plant species; morphology and anatomy; products; medical aspects; diseases; insect, bird, and mammal pests; genetics; horticulture; physiology; ecology; mensuration; and silviculture. Management recommendations and an extensive list of references are included.

Keywords: Western redcedar, *Thuja plicata,* silviculture, ecology, physiology, products.

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# Predicting Crown Weight and Bole Volume of Five Western Hardwoods

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J.A. Kendall Snell and Susan N. Little

**Authors**

J.A. KENDALL SNELL is a forester, Pacific Northwest Region, U.S. Department of Agriculture, Forest Service, P.O. Box 3623, Portland, Oregon 97208. SUSAN N. LITTLE is a research forester, Pacific Northwest Forest and Range Experiment Station, U.S. Department of Agriculture, Forest Service, 809 N.E. Sixth Avenue, Portland, Oregon 97232.

## Abstract

Snell, J.A. Kendall; Little, Susan N. Predicting crown weight and bole volume of five western hardwoods. Gen. Tech. Rep. PNW-151. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 37 p.

Regression equations are presented for estimating biomass of five western hardwoods: red alder (*Alnus rubra* Bong.), giant chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC.), bigleaf maple (*Acer macrophyllum* Pursh), Pacific madrone (*Arbutus menziesii* Pursh), and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.). Estimators are given for total crown biomass, cumulative proportions for separating crown weight into foliage and four timelag fuel diameter classes, bark weight, and bole volume (inside bark) to any specified top diameter. With one exception, the equations use diameter at breast height as the only independent variable.

Keywords: Crown weights, volume (log), volume determination methods, hardwoods, biomass.

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## Introduction

Estimates of the weight of tree foliage and branchwood and of bole volume are used for predicting total tree fiber content, for assessing wildfire hazard, and in modeling forest ecosystems. Much work has been done to quantify the weights and volumes of both conifers and hardwoods (Brown 1978, Gholz and others 1979, Grier and Logan 1977, Grier and Milne 1981, Woodard and others 1976, Young 1976, Zavitkovski and Stevens 1972). Work has also been done to separate tree biomass into timelag fuel classes which are required inputs to some wildfire behavior models (Albini 1976, Rothermel 1972).[1] Brown (1978) characterized 11 Rocky Mountain conifers by these fuel classes as did Loomis and Blank (1981) and Loomis and Roussopoulos (1978) for red oak (*Quercus rubra* L.) and aspen (*Populus tremuloides* Michx.) in Michigan and Minnesota. Wilcox and others (1982) developed a photo series for visual identification of forest residue loadings by fuel classes for the northern hardwood types. Although hardwoods comprise a large portion of the residues in the Pacific Northwest (Howard 1981), little work has been done to separate biomass of western hardwood trees into timelag fuel classes. This separation is needed for predicting wildfire behavior and for prescribing fire for site treatment.

Our objective was to develop regression equations for estimating: (1) weight of branchwood by diameter classes that correspond to timelag fuel classes, (2) weight of foliage, (3) weight of total crown, (4) volume of total bole (inside bark), and (5) volume of bole below any specified top diameter for five western hardwoods: red alder (*Alnus rubra* Bong.), giant chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC.), bigleaf maple (*Acer macrophyllum* Pursh), Pacific madrone (*Arbutus menziesii* Pursh), and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.).

## Methods

### Study Area

The study was conducted on National Forest lands in western Washington, Oregon, and northern California. Sample trees were selected from habitats common to the species being sampled. These habitats ranged from poor to good growing sites. Stocking densities around the sample trees ranged from 40 to 7,100 trees per acre.

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[1] Timelag is the time interval in which dead and down woody material loses about two-thirds of its moisture content above an equilibrium moisture content under standard drying conditions of 20 percent relative humidity and 26.7°C (Fosberg 1971).

## Field Procedures

Trees were sampled as follows:

| Number of trees sampled | D.b.h. | Age | Number of locations | Area |
|---|---|---|---|---|
| | (Inches) | (Years) | | |
| 53 red alder | 1-25 | 5-95 | 18 | Western Oregon and Washington |
| 30 giant chinkapin | 1-24 | 18-195 | 9 | Southwest Oregon and northwest California |
| 16 bigleaf maple | 2-18 | 12-114 | 8 | Western Washington |
| 31 Pacific madrone | 1-25 | 31-208 | 12 | Southwest Oregon and northwest California |
| 31 tanoak | 1-26 | 15-200 | 12 | Southwest Oregon and northwest California |

All trees in a stand at each location that were not dead, open grown, severely defoliated, or suffering from severe physical damage were candidates for sampling. Trees were sampled from late June to early September in 1979 and 1980. Increases in leaf weight caused by growth during the summer months were assumed negligible. For each sample tree, all limbs were removed before the tree was felled to avoid loss of branch material. (Because bigleaf maple and Pacific madrone have deliquescent branches, the largest limb was identified as the main bole.) As each limb was cut from the bole, the narrowest diameter at its base was measured with calipers and recorded. The limbs were then separated into live and dead branches.

Three sample branches were selected from each tree — the largest lateral branch and two randomly selected lateral branches. These sample branches were divided into leaves and into branchwood by diameter classes of 0 to 0.25, 0.25 to 1.0, 1.0 to 3.0, and 3.0 inches and larger.[2] All other live branches were weighed as a unit. All dead branches were divided into the same diameter classes, and each class was weighed separately.

Once the limbs had been removed from the bole, lengths were measured along the bole between the top of the tree and bole diameters of 1, 3, 4, 6, 7, 8, and 9 inches. The two smaller diameter classes correspond to fuel size classes, and the others correspond to timber harvest merchantability limits. For trees with diameters greater than 9 inches at ground level, additional diameters and lengths were recorded where noticeable changes in taper occurred between the 9-inch diameter point and the ground.

Disks about 1 inch thick were cut from the lower, middle, and upper portions of the bole. All bark was removed from each disk, and both the wood and bark were ovendried at 102°C for 24 hours. The weights of ovendried wood and bark were then used to determine a ratio of bark weight to wood weight.

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[2] 1-, 10-, 100-, and 1,000-hour timelag fuel classes are represented by piece diameters of 0 to 0.25, 0.25 to 1.0, 1.0 to 3.0, and 3.0 to 8 inches, respectively (Deeming and others 1977).

Samples were taken from branch components (the leaves and each size class of branchwood) of each sample branch and from each diameter class of the dead branches to determine moisture content. All samples were ovendried at 102°C for 24 hours and weighed to the nearest 0.1 gram. Any volatiles lost from foliage and bark were considered negligible.

## Calculations

The crown weight was calculated as follows: (1) The ovendry weights of sample branch components were calculated from moisture samples collected for these components. (2) These weights were regressed separately on their branch basal diameters. (3) From these regressions, the weight of each component for every branch from each tree was estimated. (4) The weight of each component was summed for all branches on each tree. (5) The total weights of these components were used as weighting factors to estimate a weighted moisture content for the whole tree. These weighted moisture percentages were then used to convert the green crown weight to estimates of ovendry weight. A similar procedure has been used by Brown (1978). Because all the dead branchwood was separated into diameter classes, the moisture samples taken from each class were used to convert them to ovendry weight. All analyses were done on ovendry weights.

For both live and dead crown, a logarithmic transformation was used to linearize the relationship between weight of the crown and d.b.h. (diameter at breast height outside bark) and to homogenize the variance about the regression line. After plotting the transformed data, the error term was assumed to be additive. The data were fit to the following model which has been commonly used in other biomass studies (Brown 1978, Gholz and others 1979, Schlaegel 1975):

$$\ln(w(i)) = A + B \ln(d); \tag{1}$$

where

$w(i)$ = $i^{th}$ weight; $w(1)$=total weight of live crown (lb), $w(2)$=total weight of dead crown (lb);
A and B = regression coefficients;
d = diameter at breast height (inches).

From the live weight of each component for each tree, cumulative fractions $f(i)$ were calculated as:

$$f(i) = T(i)/T(5); \tag{2}$$

where

$f(i)$ = $i^{th}$ cumulative fraction of live branchwood—$i$=1 to 4;
$T(1)$ = total weight of leaves;
$T(2)$ = $T(1)$+ live branchwood less than 0.25 inch in diameter;
$T(3)$ = $T(1)$+ live branchwood less than 1.0 inch in diameter;
$T(4)$ = $T(1)$+ live branchwood less than 3.0 inches in diameter; and
$T(5)$ = $T(1)$+ all live branchwood.

Plots of f(i) against d.b.h. were visually examined, and many regression models were fit to the data. Of the models fit, the one with the smallest residual mean square was:

$$f(i) = 1/(A + B\,(d)^{C}). \tag{3}$$

The measures of variability may be low because the cumulative fractions are based on indirect measurements of component weights for the whole tree.

A log transformation of the dependent variable was used to linearize the relationship between the cumulative fractions of dead branchwood and d.b.h. for red alder, giant chinkapin, and bigleaf maple, and the following regression model was used:

$$\ln(df(i)) = A + B\,(d); \tag{4}$$

where

$df(i)$ = $i^{th}$ cumulative fraction of dead branchwood — $i = 1$ to 3. Calculation of df(i) was similar to calculation of f(i).

This model did not work well for Pacific madrone and tanoak. Because a single model was not found that described the df(i) for these two species, different models were used for each cumulative fraction to achieve the best fit for our data. The df(i)'s are based on direct measurements of component weights of dead branchwood, and the variance should not be considered low as was the variance for the f(i)'s.

Smalian's formula (Avery 1967) was used for calculating the volume of each bole segment, except the section 0 to 1 inch in diameter for which a cone formula was used. Total bole volume was then obtained by summing the volume of the individual segments.

Equations for estimating the ratio (R) of bole volume below a specified top diameter to total bole volume were developed from measures of bole volumes below diameters of 1, 3, 4, 6, 7, 8, and 9 inches. The following model was used for each species:

$$R = 1 + (A(t^{B})(d^{C})); \tag{5}$$

where

R = ratio of bole volume below a specified top diameter to total bole volume;
t = specified top diameter (inches);
A, B, and C = regression coefficients.

This model was introduced by Burkhart (1977), and it compared favorably with other published models when tested by Cao and others (1980). Variability of R increases greatly as t becomes greater than d. The data were constrained to those observations with R greater than 0.5 by excluding all observations where t was equal to or greater than d.

## Results

The regression equations allow users to estimate total live and dead crown weights (tables 1 and 2) for each species.[3] The weights obtained from tables 1 and 2 may be separated into foliage or branchwood weights by diameter class (see footnote 2) by calculating the fraction of each class for a given size (d.b.h.) tree from tables 3 and 4 and then multiplying this fraction by the results obtained from tables 1 or 2 for the same tree. For estimates of individual fractions, the cumulative fractions must be subtracted from one another; for example, for fraction (F) of live branchwood weight 0 to 0.25 inch in diameter: F = f(2)-f(1) (see table 3).

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[3] Appendix 3 presents all equations in metric units.

**Table 1 — Regression equations for estimating ovendry weight of live crown for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$\ln(w) = A + B \ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -1.3290 | 2.6232 | 53 | 0.94 | 1.5563 |
| Giant chinkapin | -.8032 | 2.2699 | 30 | .94 | 1.0469 |
| Bigleaf maple | -.0582 | 2.1505 | 16 | .93 | .7252 |
| Pacific madrone | -.7881 | 2.4839 | 31 | .89 | 2.6295 |
| Tanoak | -.3169 | 2.2774 | 31 | .94 | 1.0114 |

Note: w = ovendry weight of live crown (lb); d = diameter at breast height (inches); $s^2$ = mean square error of the residuals.

**Table 2 — Regression equations for estimating dead branchwood weight of red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$\ln(dw) = A + B \ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -4.3788 | 2.6243 | 53 | 0.63 | 13.597 |
| Giant chinkapin | -2.2095 | 2.3038 | 30 | .88 | 2.390 |
| Bigleaf maple | -3.3678 | 2.5033 | 16 | .78 | 3.466 |
| Pacific madrone | -2.3938 | 2.2936 | 31 | .88 | 2.397 |
| Tanoak | -2.4895 | 2.0374 | 31 | .75 | 4.071 |

Note: dw = ovendry weight of dead branchwood weight (lb); d = diameter at breast height (inches); $s^2$ = mean square error of the residuals.

Table 3 — Regression equations for estimating cumulative fractions (f(i)) of live crown component weights for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak

$$f(i)=1/(A + B\,(d)^{C})$$

| Fraction | A | B | C | n | $s^2$ | Condition |
|---|---|---|---|---|---|---|
| | | | RED ALDER | | | |
| f(1) | 2.7638 | 0.2155 | 1.3364 | 53 | 0.0006 | None |
| f(2) | 1.2860 | .1016 | 1.3525 | 53 | .0026 | None |
| f(3) | .8847 | .0441 | 1.3021 | 53 | .0057 | If $d < 2.1$ $f(3)=1$ |
| f(4) | .9550 | .0013 | 1.9736 | 41 | .0077 | If $d < 6.1$ $f(4)=1$ |
| | | | GIANT CHINKAPIN | | | |
| f(1) | 1.6048 | .5630 | .6828 | 30 | .0008 | None |
| f(2) | 1.0700 | .2525 | .7637 | 30 | .0020 | None |
| f(3) | .7312 | .1691 | .6118 | 30 | .0034 | If $d < 2.1$ $f(3)= 1$ |
| f(4) | .9669 | .0036 | 1.1786 | 22 | .0010 | If $d < 6.6$ $f(4)= 1$ |
| | | | BIGLEAF MAPLE | | | |
| f(1) | 4.6762 | .1091 | 2.0390 | 16 | .0005 | None |
| f(2) | 3.3212 | .0777 | 2.0496 | 16 | .0009 | None |
| f(3) | .9341 | .0158 | 2.1627 | 16 | .0137 | If $d < 1.9$ $f(3)=1$ |
| f(4) | .8625 | .0093 | 1.7070 | 15 | .0092 | If $d < 4.8$ $f(4)=1$ |
| | | | PACIFIC MADRONE | | | |
| f(1) | 1.6013 | .3591 | 1.3090 | 31 | .0045 | None |
| f(2) | 1.0357 | .2263 | 1.3567 | 31 | .0115 | None |
| f(3) | 1.0281 | .0084 | 2.1850 | 30 | .0118 | None |
| f(4) | .8778 | .0115 | 1.6394 | 27 | .0132 | If $d < 4.2$ $f(4)=1$ |
| | | | TANOAK | | | |
| f(1) | 1.7936 | .5952 | .7239 | 31 | .0013 | None |
| f(2) | .9940 | .4229 | .6520 | 31 | .0034 | None |
| f(3) | .8759 | .0927 | .7843 | 31 | .0061 | If $d < 1.5$ $f(3)=1$ |
| f(4) | | | | | | $f(4)=1.0$ for all d |

Note:
$f(i)$ = cumulative fraction for the $i^{th}$ component;
$f(1)$ = fraction of leaf weight;
$f(2)$ = $f(1)$ + (fraction of 0 to 0.25 inch in d.o.b. live branchwood);
$f(3)$ = $f(1)$ + (fraction of 0 to 1.0 inch in d.o.b. live branchwood);
$f(4)$ = $f(1)$ + (fraction of 0 to 3.0 inches in d.o.b. live branchwood);
$d$ = diameter at breast height (inches); and
$s^2$ = mean square error of residuals.

**Table 4 — Regression equations for estimating cumulative fractions (df(i)) of dead crown components for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

| Fraction | n | $r^2$ | $s^2$ | Conditions |
|---|---|---|---|---|
| RED ALDER | | | | |
| $\ln(df(1))=-0.6880-0.1532(d)$ | 52 | 0.43 | 1.3243 | None |
| $\ln(df(2))= 0.2134-0.0869(d)$ | 48 | .47 | .3574 | If $d < 2.5\ df(2) =1$ |
| $\ln(df(3))= 0.3473-0.0315(d)$ | 30 | .34 | .0512 | If $d < 11.0\ df(3)=1$ |
| GIANT CHINKAPIN | | | | |
| $\ln(df(1))=-0.7695-0.0828(d)$ | 30 | .60 | .1737 | None |
| $\ln(df(2))= 0.2022-0.0564(d)$ | 29 | .72 | .0469 | If $d < 3.6\ df(2)=1$ |
| $\ln(df(3))= 0.1352-0.0160(d)$ | 19 | .28 | .0226 | If $d < 8.5\ df(3)=1$ |
| BIGLEAF MAPLE | | | | |
| $\ln(df(1))=-1.0444-0.1892(d)$ | 16 | .51 | .7589 | None |
| $\ln(df(2))= 0.0553-0.0660(d)$ | 15 | .53 | .0767 | If $d < 1.0\ df(2)=1$ |
| $\ln(df(3))= 0.0083-0.0033(d)$ | 12 | .03 | .0064 | If $d < 2.5\ df(3)=1$ |
| PACIFIC MADRONE | | | | |
| $df(1)=-0.0632+0.7214(d)^{0.25}-0.4655(\ln(d))$ | 31 | .56 | .0187 | If $d < 0.4\ df(1)=1$ |
| $df(2)=1.2671-0.1686(d)^{0.5}$ | 30 | .49 | .0321 | If $d < 2.5\ df(2)=1$ |
| $df(3)=\exp(0.0281-0.0004714(d)^2)$ | 20 | .34 | .0127 | If $d < 7.6\ df(3)=1$ |
| TANOAK | | | | |
| $df(1)=-0.1424+0.7684(d)^{0.25}-0.4730(\ln(d))$ | 31 | .54 | .0156 | If $d < 0.4\ df(1)=1$ |
| $df(2)=\exp(-2.810+4.379(d)^{0.25}-1.691(d)^{0.5})$ | 31 | .81 | .0464 | If $d < 4.1\ df(2)=1$ |
| $df(3)=1.027-0.003439(d)$ | 18 | .16 | .0023 | If $d < 7.9\ df(3)=1$ |

Note:
df(i) = cumulative fraction for the $i^{th}$ component;
df(1) = fraction of 0- to 0.25-inch in d.o.b. dead branchwood;
df(2) = fraction of 0- to 1.0-inch in d.o.b. dead branchwood;
df(3) = fraction of 0- to 3.0-inch in d.o.b. dead branchwood;
d = diameter at breast height (inches);
$s^2$ = mean square error of residuals.

**Table 5 — Regression equations for estimating total bole volume inside bark for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$\ln(v) = A + B \ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -2.9326 | 2.4999 | 53 | 0.98 | 0.8995 |
| Giant chinkapin | -3.2199 | 2.5169 | 30 | .99 | .3938 |
| Bigleaf maple | -2.7268 | 2.3050 | 16 | .97 | 7.0254 |
| Pacific madrone | -2.8331 | 2.2969 | 31 | .97 | 1.3162 |
| Tanoak | -3.2751 | 2.5010 | 31 | .98 | .9376 |

Note:
$v$ = total bole volume ($ft^3$);
$d$ = diameter at breast height (inches); and
$s^2$ = mean square error of residuals.

To obtain ovendry weight, multiply wood volume by wood density (density of red alder is 25.58 $lb/ft^3$; giant chinkapin, 26.21; bigleaf maple, 29.95; Pacific madrone, 40.31; tanoak, 41.62).

All dead crown weight came from branches less than 3 inches in d.o.b. (diameter outside bark) for all but two giant chinkapin and two bigleaf maple trees. This accounts for the low $r^2$ (0.28 for giant chinkapin and 0.03 for bigleaf maple) of the estimators for df(3) in table 4. It appears, therefore, that few giant chinkapin and bigleaf maple trees within the range of the data have dead branchwood larger than 3 inches in d.o.b.

The volume of the entire bole may be estimated from d.b.h. alone (table 5). The volume of the bole to any top diameter may be estimated by multiplying the fraction obtained from the equations in table 6 by the volume obtained from the equations in table 5. The volume may be changed to approximate weight by using average densities (Resch and Huang 1965, U.S. Forest Products Laboratory 1974).

The model presented for R in table 6 allows flexibility to estimate bole volume to any top diameter. This model gives an unbiased fit for red alder, giant chinkapin and bigleaf maple. The ratios for Pacific madrone and tanoak are slightly underestimated by the equations in table 6 for trees with d.b.h. larger than 10 inches. The estimates of variance given in table 6 provide only an indication of fit at mean d.b.h. because the variance decreased as d.b.h. increased for all species.

**Table 6 — Regression equations for estimating the ratio of bole volume below a specified top diameter to total bole volume for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$R=1+(A(t^{B})(d^{C}))$$

| Species | A | B | C | n | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -0.4280 | 3.465 | -3.269 | 258 | 0.000828 |
| Giant chinkapin | -.3741 | 3.642 | -3.406 | 133 | .000744 |
| Bigleaf maple | -.4270 | 2.348 | -2.276 | 74 | .002014 |
| Pacific madrone | -.2391 | 2.951 | -2.512 | 127 | .001032 |
| Tanoak | -.2792 | 3.038 | -2.603 | 137 | .001407 |

Note:
$R$ = the fraction of bole volume below a specified top diameter;
$t$ = specified top diameter (inches);
$d$ = diameter at breast height (inches); and
$s^2$ = mean square error of residuals.

The ratio of bark weight to wood weight calculated from analysis of disks collected in the field were plotted against disk diameter, and no apparent linear relation was found on the scatter plot. By use of the ratio of bark weight to wood weight, a mean-of-ratios estimator was calculated for each species. Estimates of these ratios and their 95-percent confidence intervals about the mean are: 0.18 ± 0.011 for red alder, 0.22 ± 0.016 for giant chinkapin, 0.14 ± 0.019 for bigleaf maple, 0.05 ± 0.009 for Pacific madrone, and 0.24 ± 0.028 for tanoak.

All the crown weight equations include bark. Extrapolation of the bark estimators to branchwood should be tested as the bark estimators are based on data collected from the bole only. If estimates of the amount of bark in the crown are critical, the user should develop local estimates based on samples taken from the crown.

## Example

The following example illustrates how to estimate the 100-hour component weight (1 to 3 inches in diameter) of a red alder tree with d.b.h. of 12 inches. It consists of three basic steps: (1) predicting total weight of live crown, dead crown, and bole; (2) predicting the fraction of the component in each total in step 1; and (3) multiplying the fractions in step 2 by the total weights in step 1.

Step 1 — predicting total weight of live crown, dead crown, and bole:

| Estimated total weight of: | Use equations in table: | Estimates for red alder: |
|---|---|---|
| Live crown | 1 | 179.4 lb |
| Dead crown | 2 | 8.5 lb |
| Bole volume | 5 | 26.6 $ft^3$ |

Bole weight = 26.6 $ft^3$ × 25.58 $lb/ft^3$ (density of red alder, U.S. Forest Products Laboratory 1974)
= 680.4 lb.

Step 2 — predicting the fraction of the component in each total in step 1:

| Estimated fraction of component from: | Use equations in table: | Estimates for red alder: |
|---|---|---|
| Live crown | 3 | (f4-f3)= 0.38 |
| Dead crown | 4 | (df3-df2)= 0.53 |
| Bole — | | |
| fraction to a 1-inch top | 6 | 0.9993 |
| fraction to a 3-inch top | 6 | -0.9943 |
| fraction of component | | 0.0050 |

Step 3 — multiplying the fractions in step 2 by the total weights in step 1:

| Estimated component weight from: | Estimates for red alder: |
|---|---|
| Live crown | (179.4 lb × 0.38) =68.2 lb |
| Dead crown | (8.5 lb × 0.53) = 4.5 lb |
| Bole | (680.4 lb × 0.005) = 3.4 lb |
| Bole + bark | (3.4 lb × 1.18) = 4.0 lb |

Total 100-hour component weight from a red alder tree 12 inches in d.b.h. is then the sum of these weights: 68.2 + 4.5 + 4.0 = 76.7 lb. Foliage and other branchwood components may also be calculated by following this procedure using the appropriate equations from the tables.

## Approximate Conversions to Metric Units

| When you know: | multiply by: | to find: |
|---|---|---|
| inches | 2.540 | centimeters |
| feet | 0.305 | meters |
| pounds | 0.454 | kilograms |
| pounds per square foot | 4.883 | kilograms per square meter |
| pounds per cubic foot | 16.019 | kilograms per cubic meter |
| tons per acre | 2.242 | metric tonnes per hectare |
| cubic feet per acre | 0.070 | cubic meters per hectare |

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## Appendix 1. Tables for Predicting Crown Weight and Bole Volume

Tables 7-27 give estimates of total crown weight, weight of branchwood by diameter class, weight of foliage, bole weight, and tip weight for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak. All weights are ovendry and are presented by 1-inch d.b.h. classes.

Total live and dead crown weights are separated into fuel classes (see footnote 2, p. 2) in tables 7-11. Tables 12-16 give the weight of bole above specified top diameters (tip weight). This weight is divided into timelag fuel classes for material less than 3 inches in d.o.b. The weight of the bole below these specified top diameters (merchantable weight) is given in tables 17-21. The top diameters in these tables (4, 5, 6, and 8 inches) are those measured in the field. Estimates for other top diameters can be developed from the equations in table 6.

Total residue weights, defined as the total crown (live and dead) weight and the weight of that portion of the bole above the specified top diameter, are given in tables 22-26.

Total tree weights for individual trees by d.b.h. class are given in table 27. These weights include the bole, bark, live crown, and dead crown.

**Table 7 — Live and dead crown weight of red alder by diameter at breast height and fuel class**

| D.b.h. | Live crown | | | | | Dead crown | | | | Total crown weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leaves | Branchwood diameter (inches) | | | | Branchwood diameter (inches) | | | | |
| | | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | |
| Inches | Ovendry pounds | | | | | | | | | |
| 1 | 0.1 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 |
| 2 | .5 | .6 | .6 | 0 | 0 | 0 | 0 | 0 | 0 | 1.7 |
| 3 | 1.3 | 1.4 | 1.7 | .3 | 0 | .1 | .1 | 0 | 0 | 4.9 |
| 4 | 2.4 | 2.7 | 3.6 | 1.3 | 0 | .1 | .3 | .1 | 0 | 10.5 |
| 5 | 3.9 | 4.4 | 6.2 | 3.5 | 0 | .2 | .5 | .2 | 0 | 18.9 |
| 6 | 5.7 | 6.3 | 9.8 | 7.4 | 0 | .3 | .7 | .4 | 0 | 30.5 |
| 7 | 7.7 | 8.5 | 14.1 | 12.7 | .7 | .4 | 1.0 | .7 | 0 | 45.7 |
| 8 | 9.9 | 10.9 | 19.3 | 19.8 | 2.0 | .4 | 1.4 | 1.1 | 0 | 64.9 |
| 9 | 12.4 | 13.4 | 25.1 | 29.0 | 4.3 | .5 | 1.8 | 1.7 | 0 | 88.3 |
| 10 | 14.9 | 16.2 | 31.7 | 40.3 | 8.0 | .6 | 2.2 | 2.5 | 0 | 116.5 |
| 11 | 17.7 | 19.0 | 39.0 | 53.8 | 13.3 | .6 | 2.6 | 3.6 | 0 | 149.5 |
| 12 | 20.5 | 22.0 | 46.9 | 69.3 | 20.7 | .7 | 3.0 | 4.5 | .3 | 187.9 |
| 13 | 23.5 | 25.1 | 55.3 | 86.8 | 30.6 | .7 | 3.5 | 5.7 | .6 | 231.8 |
| 14 | 26.6 | 28.3 | 64.2 | 106.2 | 43.4 | .8 | 3.9 | 6.9 | 1.1 | 281.5 |
| 15 | 29.8 | 31.6 | 73.7 | 127.3 | 59.7 | .8 | 4.4 | 8.4 | 1.8 | 337.4 |
| 16 | 33.1 | 35.0 | 83.6 | 150.1 | 79.8 | .8 | 4.8 | 9.9 | 2.6 | 399.6 |
| 17 | 36.5 | 38.4 | 94.0 | 174.2 | 104.2 | .8 | 5.2 | 11.6 | 3.6 | 468.5 |
| 18 | 39.9 | 41.9 | 104.7 | 199.7 | 133.3 | .8 | 5.6 | 13.4 | 4.9 | 544.3 |
| 19 | 43.4 | 45.5 | 115.9 | 226.2 | 167.7 | .8 | 6.0 | 15.4 | 6.3 | 627.2 |
| 20 | 47.0 | 49.1 | 127.4 | 253.7 | 207.8 | .8 | 6.3 | 17.5 | 8.0 | 717.5 |
| 21 | 50.7 | 52.8 | 139.2 | 281.9 | 253.9 | .7 | 6.6 | 19.6 | 10.0 | 815.5 |
| 22 | 54.4 | 56.5 | 151.4 | 310.7 | 306.5 | .7 | 6.9 | 21.9 | 12.2 | 921.4 |
| 23 | 58.2 | 60.3 | 163.9 | 340.0 | 366.0 | .7 | 7.2 | 24.3 | 14.8 | 1035.3 |
| 24 | 62.0 | 64.1 | 176.7 | 369.5 | 432.7 | .7 | 7.4 | 26.8 | 17.6 | 1157.6 |
| 25 | 65.9 | 68.0 | 189.8 | 399.3 | 507.0 | .6 | 7.6 | 29.4 | 20.8 | 1288.5 |

## Table 8 — Live and dead crown weight of giant chinkapin by diameter at breast height and fuel class

| D.b.h. | Live crown | | | | | Dead crown | | | | Total crown weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leaves | Branchwood diameter (inches) | | | | Branchwood diameter (inches) | | | | |
| | | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | |
| Inches | Ovendry pounds | | | | | | | | | |
| 1 | 0.2 | 0.1 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0.6 |
| 2 | .9 | .6 | .7 | 0 | 0 | .2 | .3 | 0 | 0 | 2.7 |
| 3 | 1.9 | 1.3 | 1.8 | .3 | 0 | .5 | .9 | 0 | 0 | 6.8 |
| 4 | 3.4 | 2.4 | 3.5 | 1.2 | 0 | .9 | 1.7 | .1 | 0 | 13.1 |
| 5 | 5.2 | 3.7 | 5.7 | 2.7 | 0 | 1.4 | 2.8 | .3 | 0 | 21.8 |
| 6 | 7.4 | 5.2 | 8.5 | 5.0 | 0 | 1.9 | 4.0 | .9 | 0 | 33.0 |
| 7 | 9.9 | 7.0 | 11.9 | 8.2 | .1 | 2.5 | 5.5 | 1.7 | 0 | 46.8 |
| 8 | 12.8 | 9.0 | 15.9 | 12.2 | .4 | 3.2 | 7.1 | 2.9 | 0 | 63.5 |
| 9 | 15.9 | 11.2 | 20.5 | 17.1 | 1.0 | 3.8 | 9.0 | 4.4 | .2 | 83.0 |
| 10 | 19.3 | 13.6 | 25.7 | 23.1 | 1.7 | 4.5 | 10.9 | 6.2 | .5 | 105.5 |
| 11 | 23.0 | 16.1 | 31.6 | 30.0 | 2.8 | 5.1 | 13.0 | 8.3 | 1.1 | 131.0 |
| 12 | 27.0 | 18.8 | 38.0 | 38.1 | 4.2 | 5.8 | 15.2 | 10.8 | 1.9 | 159.8 |
| 13 | 31.2 | 21.7 | 45.1 | 47.3 | 5.9 | 6.4 | 17.4 | 13.8 | 2.8 | 191.7 |
| 14 | 35.7 | 24.7 | 52.8 | 57.6 | 8.1 | 7.0 | 19.7 | 17.2 | 4.1 | 226.9 |
| 15 | 40.4 | 27.8 | 61.1 | 69.1 | 10.8 | 7.5 | 22.0 | 21.1 | 5.6 | 265.5 |
| 16 | 45.4 | 31.1 | 70.1 | 81.7 | 14.0 | 8.0 | 24.4 | 25.4 | 7.4 | 307.6 |
| 17 | 50.5 | 34.6 | 79.6 | 95.6 | 17.8 | 8.5 | 26.7 | 30.2 | 9.6 | 353.1 |
| 18 | 56.0 | 38.1 | 89.8 | 110.6 | 22.2 | 8.9 | 29.0 | 35.5 | 12.1 | 402.2 |
| 19 | 61.6 | 41.8 | 100.5 | 126.7 | 27.3 | 9.3 | 31.3 | 41.2 | 15.1 | 454.9 |
| 20 | 67.5 | 45.5 | 111.9 | 144.1 | 33.2 | 9.6 | 33.6 | 47.5 | 18.4 | 511.2 |
| 21 | 73.6 | 49.4 | 123.8 | 162.7 | 39.8 | 9.9 | 35.8 | 54.1 | 22.2 | 571.3 |
| 22 | 79.9 | 53.4 | 136.3 | 182.4 | 47.2 | 10.2 | 37.9 | 61.3 | 26.5 | 635.1 |
| 23 | 86.4 | 57.5 | 149.5 | 203.4 | 55.6 | 10.4 | 40.0 | 68.9 | 31.3 | 702.8 |
| 24 | 93.1 | 61.7 | 163.2 | 225.5 | 64.8 | 10.5 | 42.0 | 77.0 | 36.6 | 774.3 |
| 25 | 100.0 | 66.0 | 177.5 | 248.8 | 75.1 | 10.7 | 43.8 | 85.5 | 42.4 | 849.7 |

## Table 9 — Live and dead crown weight of bigleaf maple by diameter at breast height and fuel class

| D.b.h. | Live crown | | | | | Dead crown | | | | Total crown weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leaves | Branchwood diameter (inches) | | | | Branchwood diameter (inches) | | | | |
| | | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | |
| Inches | Ovendry pounds | | | | | | | | | |
| 1 | 0.2 | 0.1 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 |
| 2 | .8 | .3 | 3.0 | 0 | 0 | 0 | .1 | 0 | 0 | 4.4 |
| 3 | 1.8 | .7 | 6.6 | .9 | 0 | .1 | .4 | .1 | 0 | 10.6 |
| 4 | 2.9 | 1.1 | 10.9 | 3.7 | 0 | .2 | .7 | .2 | 0 | 19.7 |
| 5 | 4.0 | 1.6 | 15.2 | 9.1 | .2 | .3 | 1.2 | .4 | 0 | 32.0 |
| 6 | 5.0 | 2.0 | 19.3 | 15.7 | 2.5 | .3 | 1.8 | .8 | 0 | 47.5 |
| 7 | 5.9 | 2.3 | 22.8 | 24.3 | 6.6 | .4 | 2.6 | 1.4 | .1 | 66.5 |
| 8 | 6.7 | 2.6 | 25.8 | 34.5 | 13.0 | .5 | 3.4 | 2.3 | .1 | 88.9 |
| 9 | 7.4 | 2.9 | 28.2 | 46.1 | 21.8 | .5 | 4.4 | 3.3 | .2 | 114.8 |
| 10 | 8.0 | 3.1 | 30.2 | 58.6 | 33.6 | .6 | 5.4 | 4.7 | .3 | 144.4 |
| 11 | 8.5 | 3.2 | 31.8 | 71.8 | 48.4 | .6 | 6.5 | 6.4 | .4 | 177.7 |
| 12 | 9.0 | 3.4 | 33.1 | 85.4 | 66.6 | .6 | 7.7 | 8.5 | .5 | 214.8 |
| 13 | 9.4 | 3.5 | 34.2 | 99.2 | 88.3 | .6 | 8.9 | 11.0 | .7 | 255.7 |
| 14 | 9.7 | 3.6 | 35.0 | 113.1 | 113.6 | .6 | 10.1 | 13.9 | .9 | 300.6 |
| 15 | 10.0 | 3.7 | 35.7 | 127.0 | 142.7 | .6 | 11.3 | 17.2 | 1.2 | 349.4 |
| 16 | 10.2 | 3.8 | 36.3 | 140.7 | 175.6 | .6 | 12.5 | 21.0 | 1.6 | 402.2 |
| 17 | 10.5 | 3.9 | 36.8 | 154.2 | 212.3 | .6 | 13.7 | 25.3 | 1.9 | 459.1 |
| 18 | 10.7 | 3.9 | 37.2 | 167.5 | 253.1 | .6 | 14.9 | 30.0 | 2.4 | 520.1 |
| 19 | 10.9 | 4.0 | 37.5 | 180.4 | 297.8 | .5 | 16.0 | 35.3 | 2.9 | 585.3 |
| 20 | 11.0 | 4.0 | 37.7 | 193.1 | 346.5 | .5 | 17.1 | 41.2 | 3.5 | 654.6 |
| 21 | 11.2 | 4.1 | 38.0 | 205.5 | 399.2 | .5 | 18.1 | 47.6 | 4.2 | 728.3 |
| 22 | 11.3 | 4.1 | 38.1 | 217.5 | 456.0 | .4 | 19.1 | 54.6 | 4.9 | 806.2 |
| 23 | 11.4 | 4.1 | 38.3 | 229.3 | 516.9 | .4 | 20.1 | 62.1 | 5.8 | 888.4 |
| 24 | 11.6 | 4.2 | 38.4 | 240.7 | 581.9 | .4 | 20.9 | 70.2 | 6.7 | 975.0 |
| 25 | 11.7 | 4.2 | 38.5 | 251.8 | 651.0 | .3 | 21.8 | 79.0 | 7.8 | 1066.0 |

## Table 10 — Live and dead crown weight of Pacific madrone by diameter at breast height and fuel class

| D.b.h. | Live crown | | | | | Dead crown | | | | Total crown weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leaves | Branchwood diameter (inches) | | | | Branchwood diameter (inches) | | | | |
| | | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | |
| Inches | | | | | Ovendry pounds | | | | | |
| 1 | 0.2 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0.5 |
| 2 | 1.0 | .6 | .8 | .2 | 0 | .2 | .2 | 0 | 0 | 3.0 |
| 3 | 2.2 | 1.2 | 2.8 | .8 | 0 | .4 | .7 | 0 | 0 | 8.1 |
| 4 | 3.7 | 1.9 | 6.2 | 2.4 | 0 | .7 | 1.4 | .2 | 0 | 16.4 |
| 5 | 5.4 | 2.7 | 10.8 | 5.0 | .9 | 1.0 | 2.3 | .4 | 0 | 28.4 |
| 6 | 7.3 | 3.5 | 16.1 | 8.7 | 3.4 | 1.3 | 3.5 | .8 | 0 | 44.5 |
| 7 | 9.2 | 4.3 | 21.7 | 14.1 | 7.8 | 1.6 | 4.9 | 1.4 | 0 | 65.1 |
| 8 | 11.3 | 5.2 | 27.3 | 21.2 | 14.6 | 2.0 | 6.5 | 2.2 | 0 | 90.4 |
| 9 | 13.4 | 6.0 | 32.6 | 30.0 | 24.6 | 2.3 | 8.4 | 3.2 | .1 | 120.7 |
| 10 | 15.5 | 6.9 | 37.5 | 40.6 | 38.1 | 2.7 | 10.5 | 4.4 | .3 | 156.5 |
| 11 | 17.8 | 7.7 | 41.7 | 52.7 | 55.6 | 3.0 | 12.8 | 5.9 | .6 | 197.9 |
| 12 | 20.0 | 8.6 | 45.5 | 66.2 | 77.7 | 3.3 | 15.3 | 7.6 | 1.1 | 245.2 |
| 13 | 22.3 | 9.4 | 48.6 | 80.9 | 104.6 | 3.7 | 17.9 | 9.5 | 1.6 | 298.6 |
| 14 | 24.7 | 10.2 | 51.2 | 96.7 | 136.8 | 4.0 | 20.7 | 11.7 | 2.4 | 358.4 |
| 15 | 27.0 | 11.1 | 53.4 | 113.3 | 174.5 | 4.4 | 23.6 | 14.1 | 3.4 | 424.8 |
| 16 | 29.4 | 11.9 | 55.0 | 130.7 | 218.2 | 4.7 | 26.6 | 16.8 | 4.7 | 498.0 |
| 17 | 31.9 | 12.8 | 56.3 | 148.6 | 268.1 | 5.0 | 29.6 | 19.7 | 6.2 | 578.3 |
| 18 | 34.3 | 13.6 | 57.3 | 167.1 | 324.4 | 5.3 | 32.8 | 22.9 | 8.1 | 665.7 |
| 19 | 36.8 | 14.4 | 57.9 | 185.9 | 387.4 | 5.7 | 36.0 | 26.2 | 10.4 | 760.6 |
| 20 | 39.3 | 15.2 | 58.2 | 205.0 | 457.4 | 6.0 | 39.2 | 29.8 | 13.0 | 863.1 |
| 21 | 41.8 | 16.1 | 58.2 | 224.4 | 534.5 | 6.3 | 42.4 | 33.6 | 16.2 | 973.4 |
| 22 | 44.4 | 16.9 | 58.1 | 243.9 | 618.9 | 6.6 | 45.5 | 37.5 | 19.9 | 1091.6 |
| 23 | 46.9 | 17.7 | 57.7 | 263.6 | 710.8 | 6.9 | 48.7 | 41.6 | 24.1 | 1218.0 |
| 24 | 49.5 | 18.5 | 57.1 | 283.4 | 810.5 | 7.2 | 51.7 | 45.8 | 28.9 | 1352.8 |
| 25 | 52.1 | 19.4 | 56.4 | 303.3 | 918.1 | 7.6 | 54.7 | 50.2 | 34.3 | 1496.0 |

## Table 11 — Live and dead crown weight of tanoak by diameter at breast height and fuel class

| D.b.h. | Live crown | | | | | Dead crown | | | | Total crown weight |
|---|---|---|---|---|---|---|---|---|---|---|
| | Leaves | Branchwood diameter (inches) | | | | Branchwood diameter (inches) | | | | |
| | | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | 0-0.24 | 0.25-0.99 | 1-2.99 | ≥3 | |
| Inches | | | | | Ovendry pounds | | | | | |
| 1 | 0.3 | 0.2 | 0.2 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0.8 |
| 2 | 1.3 | .9 | 1.3 | .1 | 0 | .2 | .2 | 0 | 0 | 3.9 |
| 3 | 2.9 | 1.9 | 3.3 | .8 | 0 | .3 | .5 | 0 | 0 | 9.7 |
| 4 | 5.0 | 3.4 | 6.5 | 2.2 | 0 | .4 | 1.0 | 0 | 0 | 18.5 |
| 5 | 7.7 | 5.2 | 10.7 | 4.8 | 0 | .5 | 1.6 | .1 | 0 | 30.7 |
| 6 | 10.9 | 7.5 | 16.1 | 8.7 | 0 | .7 | 2.2 | .3 | 0 | 46.3 |
| 7 | 14.5 | 10.0 | 22.5 | 14.2 | 0 | .8 | 2.9 | .7 | 0 | 65.6 |
| 8 | 18.5 | 13.0 | 30.0 | 21.5 | 0 | 1.0 | 3.6 | 1.2 | 0 | 88.7 |
| 9 | 23.0 | 16.2 | 38.5 | 30.7 | 0 | 1.1 | 4.3 | 1.9 | 0 | 115.8 |
| 10 | 27.9 | 19.8 | 48.1 | 42.2 | 0 | 1.2 | 5.0 | 2.7 | .1 | 147.0 |
| 11 | 33.2 | 23.7 | 58.6 | 55.9 | 0 | 1.3 | 5.7 | 3.8 | .1 | 182.4 |
| 12 | 38.8 | 28.0 | 70.1 | 72.1 | 0 | 1.5 | 6.3 | 5.1 | .2 | 222.1 |
| 13 | 44.7 | 32.5 | 82.6 | 90.9 | 0 | 1.6 | 6.9 | 6.6 | .3 | 266.2 |
| 14 | 51.1 | 37.4 | 95.9 | 112.5 | 0 | 1.7 | 7.5 | 8.4 | .4 | 314.8 |
| 15 | 57.7 | 42.5 | 110.2 | 137.0 | 0 | 1.8 | 8.0 | 10.3 | .5 | 368.0 |
| 16 | 64.7 | 48.0 | 125.2 | 164.5 | 0 | 2.0 | 8.5 | 12.5 | .7 | 425.9 |
| 17 | 71.9 | 53.7 | 141.2 | 195.1 | 0 | 2.1 | 8.9 | 14.9 | .8 | 488.6 |
| 18 | 79.5 | 59.8 | 157.9 | 229.0 | 0 | 2.2 | 9.2 | 17.5 | 1.0 | 556.1 |
| 19 | 87.4 | 66.1 | 175.5 | 266.2 | 0 | 2.3 | 9.5 | 20.3 | 1.3 | 628.6 |
| 20 | 95.6 | 72.7 | 193.8 | 306.8 | 0 | 2.4 | 9.8 | 23.4 | 1.6 | 706.0 |
| 21 | 104.0 | 79.5 | 212.9 | 351.0 | 0 | 2.6 | 10.0 | 26.6 | 1.9 | 788.5 |
| 22 | 112.7 | 86.7 | 232.8 | 398.8 | 0 | 2.7 | 10.1 | 30.1 | 2.2 | 876.1 |
| 23 | 121.7 | 94.1 | 253.3 | 450.4 | 0 | 2.8 | 10.2 | 33.7 | 2.6 | 968.9 |
| 24 | 131.0 | 101.8 | 274.6 | 505.8 | 0 | 3.0 | 10.3 | 37.6 | 3.0 | 1066.9 |
| 25 | 140.5 | 109.7 | 296.6 | 565.0 | 0 | 3.1 | 10.3 | 41.6 | 3.4 | 1170.3 |

## Table 12 — Weight of bole tips of red alder by size class and top diameters outside bark of 4, 5, 6, and 8 inches

| D.b.h. | Weight of tip ≤3 inches in d.o.b. between diameters of (inches): | | | | Weight of tip >3 inches in d.o.b. to a top diameter of (inches): | | | | Total weight of tip above a top diameter of (inches): | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-0.25 | 0.25-1 | 1-3 | 0-3 | 4 | 5 | 6 | 8 | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | | | | | | | | |
| 1 | 0 | 0.68 | 0.92 | 1.6 | 0 | 0 | 0 | 0 | 1.6 | 1.6 | 1.6 | 1.6 |
| 2 | 0 | .40 | 8.69 | 9.1 | 0 | 0 | 0 | 0 | 9.1 | 9.1 | 9.1 | 9.1 |
| 3 | 0 | .29 | 13.01 | 13.3 | 11.8 | 11.8 | 11.8 | 11.8 | 25.1 | 25.1 | 25.1 | 25.1 |
| 4 | 0 | .23 | 10.43 | 10.7 | 18.2 | 40.8 | 40.8 | 40.8 | 28.9 | 51.4 | 51.4 | 51.4 |
| 5 | 0 | .20 | 8.78 | 9.0 | 15.4 | 43.7 | 80.9 | 80.9 | 24.3 | 52.7 | 89.9 | 89.9 |
| 6 | 0 | .17 | 7.63 | 7.8 | 13.3 | 38.0 | 78.4 | 133.9 | 21.2 | 45.8 | 86.2 | 141.8 |
| 7 | 0 | .15 | 6.78 | 6.9 | 11.9 | 33.8 | 69.6 | 200.5 | 18.8 | 40.7 | 76.6 | 207.5 |
| 8 | 0 | .14 | 6.12 | 6.3 | 10.7 | 30.5 | 62.8 | 181.0 | 17.0 | 36.7 | 69.1 | 187.2 |
| 9 | 0 | .13 | 5.59 | 5.7 | 9.8 | 27.8 | 57.4 | 165.3 | 15.5 | 33.6 | 63.1 | 171.0 |
| 10 | 0 | .12 | 5.15 | 5.3 | 9.0 | 25.7 | 52.9 | 152.4 | 14.3 | 30.9 | 58.2 | 157.7 |
| 11 | 0 | .11 | 4.79 | 4.9 | 8.4 | 23.9 | 49.2 | 141.6 | 13.3 | 28.8 | 54.1 | 146.5 |
| 12 | 0 | .10 | 4.48 | 4.6 | 7.8 | 22.3 | 46.0 | 132.5 | 12.4 | 26.9 | 50.6 | 137.1 |
| 13 | 0 | .09 | 4.21 | 4.3 | 7.4 | 21.0 | 43.3 | 124.6 | 11.7 | 25.3 | 47.6 | 128.9 |
| 14 | 0 | .09 | 3.98 | 4.1 | 7.0 | 19.8 | 40.9 | 117.7 | 11.0 | 23.9 | 44.9 | 121.7 |
| 15 | 0 | .09 | 3.77 | 3.9 | 6.6 | 18.8 | 38.7 | 111.6 | 10.5 | 22.7 | 42.6 | 115.4 |
| 16 | 0 | .08 | 3.59 | 3.7 | 6.3 | 17.9 | 36.9 | 106.2 | 9.9 | 21.6 | 40.5 | 109.9 |
| 17 | 0 | .08 | 3.43 | 3.5 | 6.0 | 17.1 | 35.2 | 101.3 | 9.5 | 20.6 | 38.7 | 104.8 |
| 18 | 0 | .07 | 3.28 | 3.4 | 5.7 | 16.3 | 33.7 | 97.0 | 9.1 | 19.7 | 37.0 | 100.3 |
| 19 | 0 | .07 | 3.15 | 3.2 | 5.5 | 15.7 | 32.3 | 93.0 | 8.7 | 18.9 | 35.5 | 96.2 |
| 20 | 0 | .07 | 3.02 | 3.1 | 5.3 | 15.1 | 31.1 | 89.4 | 8.4 | 18.2 | 34.1 | 92.5 |
| 21 | 0 | .07 | 2.91 | 3.0 | 5.1 | 14.5 | 29.9 | 86.1 | 8.1 | 17.5 | 32.9 | 89.1 |
| 22 | 0 | .06 | 2.81 | 2.9 | 4.9 | 14.0 | 28.9 | 83.1 | 7.8 | 16.9 | 31.7 | 86.0 |
| 23 | 0 | .06 | 2.72 | 2.8 | 4.7 | 13.5 | 27.9 | 80.3 | 7.5 | 16.3 | 30.7 | 83.1 |
| 24 | 0 | .06 | 2.63 | 2.7 | 4.6 | 13.1 | 27.0 | 77.7 | 7.3 | 15.8 | 29.7 | 80.4 |
| 25 | 0 | .06 | 2.55 | 2.6 | 4.5 | 12.7 | 26.2 | 75.3 | 7.1 | 15.3 | 28.8 | 77.9 |

## Table 13 — Weight of bole tips of giant chinkapin by size class and top diameters outside bark of 4, 5, 6, and 8 inches

| D.b.h. | Weight of tip ≤3 inches in d.o.b. between diameters of (inches): | | | | Weight of tip >3 inches in d.o.b. to a top diameter of (inches): | | | | Total weight of tip above a top diameter of (inches): | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-0.25 | 0.25-1 | 1-3 | 0-3 | 4 | 5 | 6 | 8 | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | | | | | | | | |
| 1 | 0 | 0.47 | 0.80 | 1.3 | 0 | 0 | 0 | 0 | 1.3 | 1.3 | 1.3 | 1.3 |
| 2 | 0 | .26 | 7.05 | 7.3 | 0 | 0 | 0 | 0 | 7.3 | 7.3 | 7.3 | 7.3 |
| 3 | 0 | .18 | 9.66 | 9.8 | 10.5 | 10.5 | 10.5 | 10.5 | 20.3 | 20.3 | 20.3 | 20.3 |
| 4 | 0 | .14 | 7.48 | 7.6 | 14.1 | 34.2 | 34.2 | 34.2 | 21.7 | 41.9 | 41.9 | 41.9 |
| 5 | 0 | .11 | 6.13 | 6.2 | 11.6 | 33.9 | 67.1 | 67.1 | 17.8 | 40.1 | 73.4 | 73.4 |
| 6 | 0 | .10 | 5.21 | 5.3 | 9.8 | 28.8 | 61.0 | 110.8 | 15.1 | 34.1 | 66.3 | 116.1 |
| 7 | 0 | .08 | 4.55 | 4.6 | 8.6 | 25.1 | 53.2 | 160.2 | 13.2 | 29.8 | 57.8 | 164.8 |
| 8 | 0 | .07 | 4.04 | 4.1 | 7.6 | 22.3 | 47.2 | 142.3 | 11.7 | 26.4 | 51.3 | 146.4 |
| 9 | 0 | .07 | 3.64 | 3.7 | 6.9 | 20.1 | 42.5 | 128.1 | 10.6 | 23.8 | 46.2 | 131.8 |
| 10 | 0 | .06 | 3.31 | 3.4 | 6.2 | 18.3 | 38.7 | 116.7 | 9.6 | 21.7 | 42.1 | 120.0 |
| 11 | 0 | .06 | 3.04 | 3.1 | 5.7 | 16.8 | 35.6 | 107.2 | 8.8 | 19.9 | 38.7 | 110.3 |
| 12 | 0 | .05 | 2.82 | 2.9 | 5.3 | 15.6 | 32.9 | 99.2 | 8.2 | 18.4 | 35.8 | 102.1 |
| 13 | 0 | .05 | 2.62 | 2.7 | 4.9 | 14.5 | 30.7 | 92.4 | 7.6 | 17.2 | 33.3 | 95.1 |
| 14 | 0 | .05 | 2.45 | 2.5 | 4.6 | 13.6 | 28.7 | 86.5 | 7.1 | 16.1 | 31.2 | 89.0 |
| 15 | 0 | .04 | 2.31 | 2.4 | 4.4 | 12.8 | 27.0 | 81.4 | 6.7 | 15.1 | 29.4 | 83.7 |
| 16 | 0 | .04 | 2.18 | 2.2 | 4.1 | 12.1 | 25.5 | 76.8 | 6.3 | 14.3 | 27.7 | 79.0 |
| 17 | 0 | .04 | 2.07 | 2.1 | 3.9 | 11.4 | 24.2 | 72.8 | 6.0 | 13.5 | 26.3 | 74.9 |
| 18 | 0 | .04 | 1.96 | 2.0 | 3.7 | 10.9 | 23.0 | 69.2 | 5.7 | 12.9 | 25.0 | 71.2 |
| 19 | 0 | .03 | 1.87 | 1.9 | 3.5 | 10.3 | 21.9 | 65.9 | 5.4 | 12.2 | 23.8 | 67.8 |
| 20 | 0 | .03 | 1.79 | 1.8 | 3.4 | 9.9 | 20.9 | 63.0 | 5.2 | 11.7 | 22.7 | 64.8 |
| 21 | 0 | .03 | 1.71 | 1.7 | 3.2 | 9.5 | 20.0 | 60.3 | 5.0 | 11.2 | 21.8 | 62.1 |
| 22 | 0 | .03 | 1.64 | 1.7 | 3.1 | 9.1 | 19.2 | 57.9 | 4.8 | 10.8 | 20.9 | 59.6 |
| 23 | 0 | .03 | 1.58 | 1.6 | 3.0 | 8.7 | 18.5 | 55.6 | 4.6 | 10.3 | 20.1 | 57.2 |
| 24 | 0 | .03 | 1.52 | 1.5 | 2.9 | 8.4 | 17.8 | 53.6 | 4.4 | 10.0 | 19.3 | 55.1 |
| 25 | 0 | .03 | 1.47 | 1.5 | 2.8 | 8.1 | 17.1 | 51.7 | 4.3 | 9.6 | 18.6 | 53.2 |

Table 14 — Weight of bole tips of bigleaf maple by size class and top diameters outside bark of 4, 5, 6, and 8 inches

| D.b.n. | Weight of tip ≤3 inches in d.o.b. between diameters of (inches): | | | | Weight of tip >3 inches in d.o.b. to a top diameter of (inches): | | | | Total weight of tip above a top diameter of (inches): | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-0.25 | 0.25-1 | 1-3 | 0-3 | 4 | 5 | 6 | 8 | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | | | | | | | | |
| 1 | 0 | 0.92 | 1.28 | 2.2 | 0 | 0 | 0 | 0 | 2.2 | 2.2 | 2.2 | 2.2 |
| 2 | 0 | .94 | 10.07 | 11.0 | 0 | 0 | 0 | 0 | 11.0 | 11.0 | 11.0 | 11.0 |
| 3 | 0 | .95 | 12.01 | 13.0 | 12.5 | 15.1 | 15.1 | 15.1 | 25.5 | 28.1 | 28.1 | 28.1 |
| 4 | 0 | .95 | 12.11 | 13.1 | 12.6 | 30.4 | 41.5 | 41.5 | 25.7 | 43.5 | 54.6 | 54.6 |
| 5 | 0 | .96 | 12.19 | 13.2 | 12.7 | 30.6 | 53.9 | 78.1 | 25.9 | 43.7 | 67.1 | 91.2 |
| 6 | 0 | .97 | 12.25 | 13.3 | 12.8 | 30.7 | 54.2 | 119.3 | 26.0 | 44.0 | 67.5 | 132.6 |
| 7 | 0 | .97 | 12.30 | 13.3 | 12.8 | 30.9 | 54.5 | 119.9 | 26.2 | 44.2 | 67.8 | 133.2 |
| 8 | 0 | .97 | 12.35 | 13.4 | 12.9 | 31.0 | 54.7 | 120.3 | 26.3 | 44.4 | 68.0 | 133.7 |
| 9 | 0 | .98 | 12.39 | 13.4 | 12.9 | 31.1 | 54.9 | 120.8 | 26.4 | 44.5 | 68.3 | 134.2 |
| 10 | 0 | .98 | 12.43 | 13.5 | 13.0 | 31.2 | 55.0 | 121.1 | 26.4 | 44.6 | 68.5 | 134.6 |
| 11 | 0 | .98 | 12.47 | 13.5 | 13.0 | 31.3 | 55.2 | 121.5 | 26.5 | 44.8 | 68.7 | 135.0 |
| 12 | 0 | .99 | 12.50 | 13.5 | 13.1 | 31.4 | 55.3 | 121.8 | 26.6 | 44.9 | 68.9 | 135.3 |
| 13 | 0 | .99 | 12.53 | 13.6 | 13.1 | 31.4 | 55.5 | 122.1 | 26.6 | 45.0 | 69.0 | 135.6 |
| 14 | 0 | .99 | 12.55 | 13.6 | 13.1 | 31.5 | 55.6 | 122.3 | 26.7 | 45.1 | 69.2 | 135.9 |
| 15 | 0 | .99 | 12.58 | 13.6 | 13.1 | 31.6 | 55.7 | 122.6 | 26.7 | 45.2 | 69.3 | 136.2 |
| 16 | 0 | .99 | 12.60 | 13.6 | 13.2 | 31.6 | 55.8 | 122.8 | 26.8 | 45.3 | 69.4 | 136.4 |
| 17 | 0 | 1.00 | 12.63 | 13.7 | 13.2 | 31.7 | 55.9 | 123.0 | 26.8 | 45.3 | 69.6 | 136.7 |
| 18 | 0 | 1.00 | 12.65 | 13.7 | 13.2 | 31.7 | 56.0 | 123.2 | 26.9 | 45.4 | 69.7 | 136.9 |
| 19 | 0 | 1.00 | 12.67 | 13.7 | 13.2 | 31.8 | 56.1 | 123.4 | 26.9 | 45.5 | 69.8 | 137.1 |
| 20 | 0 | 1.00 | 12.69 | 13.7 | 13.2 | 31.8 | 56.2 | 123.6 | 27.0 | 45.5 | 69.9 | 137.3 |
| 21 | 0 | 1.00 | 12.70 | 13.7 | 13.3 | 31.9 | 56.2 | 123.8 | 27.0 | 45.6 | 70.0 | 137.5 |
| 22 | 0 | 1.00 | 12.72 | 13.8 | 13.3 | 31.9 | 56.3 | 123.9 | 27.0 | 45.7 | 70.1 | 137.7 |
| 23 | 0 | 1.00 | 12.74 | 13.8 | 13.3 | 31.9 | 56.4 | 124.1 | 27.1 | 45.7 | 70.2 | 137.9 |
| 24 | 0 | 1.01 | 12.75 | 13.8 | 13.3 | 32.0 | 56.5 | 124.2 | 27.1 | 45.8 | 70.3 | 138.0 |
| 25 | 0 | 1.01 | 12.77 | 13.8 | 13.3 | 32.0 | 56.5 | 124.4 | 27.1 | 45.8 | 70.3 | 138.2 |

**Table 15 — Weight of bole tips of Pacific madrone by size class and top diameters outside bark of 4, 5, 6, and 8 inches**

| D.b.h. | Weight of tip ≤3 inches in d.o.b. between diameters of (inches): | | | | Weight of tip >3 inches in d.o.b. to a top diameter of (inches): | | | | Total weight of tip above a top diameter of (inches): | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-0.25 | 0.25-1 | 1-3 | 0-3 | 4 | 5 | 6 | 8 | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | | | | | | | | |
| 1 | 0.01 | 0.59 | 1.89 | 2.5 | 0 | 0 | 0 | 0 | 2.5 | 2.5 | 2.5 | 2.5 |
| 2 | .01 | .50 | 11.72 | 12.2 | 0 | 0 | 0 | 0 | 12.2 | 12.2 | 12.2 | 12.2 |
| 3 | .01 | .46 | 11.56 | 12.0 | 16.1 | 19.0 | 19.0 | 19.0 | 28.1 | 31.1 | 31.1 | 31.1 |
| 4 | .01 | .43 | 10.86 | 11.3 | 15.1 | 39.7 | 48.8 | 48.8 | 26.4 | 51.0 | 60.1 | 60.1 |
| 5 | .01 | .41 | 10.35 | 10.8 | 14.4 | 37.9 | 72.5 | 89.6 | 25.2 | 48.7 | 83.3 | 100.4 |
| 6 | .01 | .40 | 9.96 | 10.4 | 13.9 | 36.4 | 69.8 | 142.2 | 24.2 | 46.8 | 80.1 | 152.6 |
| 7 | .01 | .39 | 9.63 | 10.0 | 13.4 | 35.2 | 67.5 | 171.1 | 23.4 | 45.3 | 77.5 | 181.1 |
| 8 | .01 | .37 | 9.36 | 9.7 | 13.0 | 34.2 | 65.6 | 166.3 | 22.8 | 44.0 | 75.3 | 176.0 |
| 9 | .01 | .36 | 9.12 | 9.5 | 12.7 | 33.4 | 63.9 | 162.1 | 22.2 | 42.9 | 73.4 | 171.6 |
| 10 | .01 | .36 | 8.92 | 9.3 | 12.4 | 32.6 | 62.5 | 158.5 | 21.7 | 41.9 | 71.8 | 167.8 |
| 11 | .01 | .35 | 8.74 | 9.1 | 12.2 | 32.0 | 61.2 | 155.3 | 21.3 | 41.1 | 70.3 | 164.4 |
| 12 | .01 | .34 | 8.58 | 8.9 | 11.9 | 31.4 | 60.1 | 152.4 | 20.9 | 40.3 | 69.0 | 161.3 |
| 13 | .01 | .34 | 8.43 | 8.8 | 11.7 | 30.8 | 59.1 | 149.8 | 20.5 | 39.6 | 67.8 | 158.6 |
| 14 | .01 | .33 | 8.30 | 8.6 | 11.5 | 30.4 | 58.1 | 147.4 | 20.2 | 39.0 | 66.8 | 156.1 |
| 15 | .01 | .33 | 8.17 | 8.5 | 11.4 | 29.9 | 57.3 | 145.2 | 19.9 | 38.4 | 65.8 | 153.8 |
| 16 | .01 | .32 | 8.06 | 8.4 | 11.2 | 29.5 | 56.5 | 143.2 | 19.6 | 37.9 | 64.9 | 151.6 |
| 17 | .01 | .32 | 7.96 | 8.3 | 11.1 | 29.1 | 55.8 | 141.4 | 19.4 | 37.4 | 64.0 | 149.7 |
| 18 | .01 | .31 | 7.86 | 8.2 | 10.9 | 28.8 | 55.1 | 139.7 | 19.1 | 36.9 | 63.3 | 147.8 |
| 19 | .01 | .31 | 7.77 | 8.1 | 10.8 | 28.4 | 54.4 | 138.0 | 18.9 | 36.5 | 62.5 | 146.1 |
| 20 | .01 | .31 | 7.68 | 8.0 | 10.7 | 28.1 | 53.8 | 136.5 | 18.7 | 36.1 | 61.8 | 144.5 |
| 21 | .01 | .30 | 7.60 | 7.9 | 10.6 | 27.8 | 53.3 | 135.1 | 18.5 | 35.7 | 61.2 | 143.0 |
| 22 | .01 | .30 | 7.53 | 7.8 | 10.5 | 27.5 | 52.7 | 133.8 | 18.3 | 35.4 | 60.6 | 141.6 |
| 23 | .01 | .30 | 7.46 | 7.8 | 10.4 | 27.3 | 52.2 | 132.5 | 18.1 | 35.0 | 60.0 | 140.2 |
| 24 | .01 | .30 | 7.39 | 7.7 | 10.3 | 27.0 | 51.8 | 131.3 | 18.0 | 34.7 | 59.5 | 139.0 |
| 25 | 0 | .29 | 7.32 | 7.6 | 10.2 | 26.8 | 51.3 | 130.1 | 17.8 | 34.4 | 58.9 | 137.8 |

## Table 16 — Weight of bole tips of tanoak by size class and top diameters outside bark of 4, 5, 6, and 8 inches

| D.b.h. | Weight of tip ≤3 inches in d.o.b. between diameters of (inches): | | | | Weight of tip >3 inches in d.o.b. to a top diameter of (inches): | | | | Total weight of tip above a top diameter of (inches): | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-0.25 | 0.25-1 | 1-3 | 0-3 | 4 | 5 | 6 | 8 | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | | | | | | | | |
| 1 | 0.01 | 0.54 | 1.41 | 2.0 | 0 | 0 | 0 | 0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 2 | .01 | .50 | 10.54 | 11.0 | 0 | 0 | 0 | 0 | 11.0 | 11.0 | 11.0 | 11.0 |
| 3 | .01 | .48 | 13.23 | 13.7 | 16.7 | 16.7 | 16.7 | 16.7 | 30.5 | 30.5 | 30.5 | 30.5 |
| 4 | .01 | .47 | 12.84 | 13.3 | 18.6 | 49.2 | 49.2 | 49.2 | 31.9 | 62.5 | 62.5 | 62.5 |
| 5 | .01 | .46 | 12.55 | 13.0 | 18.2 | 48.4 | 93.9 | 96.3 | 31.2 | 61.4 | 106.9 | 109.3 |
| 6 | .01 | .45 | 12.32 | 12.8 | 17.8 | 47.5 | 92.2 | 159.6 | 30.6 | 60.3 | 104.9 | 172.4 |
| 7 | .01 | .44 | 12.13 | 12.6 | 17.6 | 46.8 | 90.7 | 235.0 | 30.1 | 59.4 | 103.3 | 247.6 |
| 8 | .01 | .43 | 11.97 | 12.4 | 17.3 | 46.2 | 89.5 | 231.8 | 29.7 | 58.6 | 101.9 | 244.2 |
| 9 | .01 | .43 | 11.82 | 12.3 | 17.1 | 45.6 | 88.4 | 229.0 | 29.4 | 57.9 | 100.7 | 241.3 |
| 10 | .01 | .42 | 11.70 | 12.1 | 16.9 | 45.1 | 87.5 | 226.6 | 29.1 | 57.2 | 99.6 | 238.7 |
| 11 | .01 | .42 | 11.58 | 12.0 | 16.8 | 44.7 | 86.6 | 224.4 | 28.8 | 56.7 | 98.6 | 236.4 |
| 12 | .01 | .42 | 11.48 | 11.9 | 16.6 | 44.3 | 85.9 | 222.4 | 28.5 | 56.2 | 97.8 | 234.3 |
| 13 | .01 | .41 | 11.39 | 11.8 | 16.5 | 43.9 | 85.2 | 220.6 | 28.3 | 55.7 | 97.0 | 232.4 |
| 14 | .01 | .41 | 11.30 | 11.7 | 16.4 | 43.6 | 84.5 | 218.9 | 28.1 | 55.3 | 96.3 | 230.7 |
| 15 | .01 | .41 | 11.22 | 11.6 | 16.2 | 43.3 | 83.9 | 217.4 | 27.9 | 54.9 | 95.6 | 229.0 |
| 16 | .01 | .40 | 11.15 | 11.6 | 16.1 | 43.0 | 83.4 | 216.0 | 27.7 | 54.6 | 94.9 | 227.5 |
| 17 | .01 | .40 | 11.08 | 11.5 | 16.0 | 42.7 | 82.9 | 214.6 | 27.5 | 54.2 | 94.4 | 226.1 |
| 18 | .01 | .40 | 11.02 | 11.4 | 16.0 | 42.5 | 82.4 | 213.4 | 27.4 | 53.9 | 93.8 | 224.8 |
| 19 | .01 | .40 | 10.96 | 11.4 | 15.9 | 42.3 | 81.9 | 212.2 | 27.2 | 53.6 | 93.3 | 223.6 |
| 20 | .01 | .40 | 10.90 | 11.3 | 15.8 | 42.0 | 81.5 | 211.1 | 27.1 | 53.3 | 92.8 | 222.4 |
| 21 | .01 | .39 | 10.84 | 11.2 | 15.7 | 41.8 | 81.1 | 210.1 | 26.9 | 53.1 | 92.4 | 221.3 |
| 22 | .01 | .39 | 10.79 | 11.2 | 15.6 | 41.6 | 80.7 | 209.1 | 26.8 | 52.8 | 91.9 | 220.3 |
| 23 | .01 | .39 | 10.74 | 11.1 | 15.6 | 41.4 | 80.4 | 208.1 | 26.7 | 52.6 | 91.5 | 219.3 |
| 24 | .01 | .39 | 10.70 | 11.1 | 15.5 | 41.3 | 80.0 | 207.2 | 26.6 | 52.4 | 91.1 | 218.3 |
| 25 | .01 | .39 | 10.65 | 11.0 | 15.4 | 41.1 | 79.7 | 206.4 | 26.5 | 52.1 | 90.7 | 217.4 |

## Table 17 — Bole weight of red alder to top diameters outside bark and total bole weight, by diameter at breast height outside bark[1]

| D.b.h. | Bole weight to a top diameter of (inches): | | | | Total bole |
|---|---|---|---|---|---|
| | 4 | 5 | 6 | 8 | |
| Inches | Ovendry pounds | | | | |
| 1 | 0 | 0 | 0 | 0 | 1.6 |
| 2 | 0 | 0 | 0 | 0 | 9.1 |
| 3 | 0 | 0 | 0 | 0 | 25.1 |
| 4 | 22.6 | 0 | 0 | 0 | 51.4 |
| 5 | 65.5 | 37.1 | 0 | 0 | 89.9 |
| 6 | 120.6 | 95.9 | 55.6 | 0 | 141.8 |
| 7 | 189.6 | 167.7 | 131.8 | .9 | 208.4 |
| 8 | 274.0 | 254.3 | 221.9 | 103.8 | 291.0 |
| 9 | 375.1 | 357.1 | 327.5 | 219.6 | 390.6 |
| 10 | 494.0 | 477.4 | 450.1 | 350.6 | 508.3 |
| 11 | 631.8 | 616.3 | 591.0 | 498.5 | 645.1 |
| 12 | 789.4 | 774.9 | 751.3 | 664.8 | 801.8 |
| 13 | 967.8 | 954.2 | 931.9 | 850.6 | 979.5 |
| 14 | 1167.8 | 1154.9 | 1133.9 | 1057.1 | 1178.8 |
| 15 | 1390.3 | 1378.1 | 1358.1 | 1285.3 | 1400.7 |
| 16 | 1636.0 | 1624.4 | 1605.4 | 1536.1 | 1646.0 |
| 17 | 1905.8 | 1894.7 | 1876.6 | 1810.5 | 1915.3 |
| 18 | 2200.4 | 2189.8 | 2172.5 | 2109.2 | 2209.5 |
| 19 | 2520.6 | 2510.4 | 2493.7 | 2433.0 | 2529.3 |
| 20 | 2866.9 | 2857.1 | 2841.2 | 2782.8 | 2875.3 |
| 21 | 3240.2 | 3230.8 | 3215.4 | 3159.2 | 3248.3 |
| 22 | 3641.1 | 3632.0 | 3617.2 | 3562.9 | 3648.9 |
| 23 | 4070.2 | 4061.5 | 4047.1 | 3994.7 | 4077.8 |
| 24 | 4528.3 | 4519.8 | 4505.9 | 4455.1 | 4535.5 |
| 25 | 5015.8 | 5007.5 | 4994.1 | 4944.9 | 5022.8 |

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[1] Bole weight was calculated from ground level to given top diameter.

## Table 18 — Bole weight of giant chinkapin to top diameters outside bark and total bole weight, by diameter at breast height outside bark[1]

| D.b.h. | Bole weight to a top diameter of (inches): | | | | Total bole |
|---|---|---|---|---|---|
| | 4 | 5 | 6 | 8 | |
| Inches | Ovendry pounds | | | | |
| 1 | 0 | 0 | 0 | 0 | 1.3 |
| 2 | 0 | 0 | 0 | 0 | 7.3 |
| 3 | 0 | 0 | 0 | 0 | 20.3 |
| 4 | 20.1 | 0 | 0 | 0 | 41.9 |
| 5 | 55.6 | 33.3 | 0 | 0 | 73.4 |
| 6 | 101.0 | 82.0 | 49.8 | 0 | 116.1 |
| 7 | 158.0 | 141.4 | 113.4 | 6.3 | 171.2 |
| 8 | 227.8 | 213.1 | 188.2 | 93.2 | 239.5 |
| 9 | 311.7 | 298.4 | 276.0 | 190.4 | 322.2 |
| 10 | 410.4 | 398.4 | 378.0 | 300.0 | 420.1 |
| 11 | 525.1 | 514.0 | 495.3 | 423.6 | 533.9 |
| 12 | 656.5 | 646.2 | 628.9 | 562.6 | 664.7 |
| 13 | 805.4 | 795.8 | 779.7 | 717.9 | 813.0 |
| 14 | 972.6 | 963.6 | 948.5 | 890.7 | 979.7 |
| 15 | 1158.8 | 1150.4 | 1136.1 | 1081.8 | 1165.5 |
| 16 | 1364.7 | 1356.8 | 1343.3 | 1292.0 | 1371.1 |
| 17 | 1591.1 | 1583.6 | 1570.8 | 1522.2 | 1597.1 |
| 18 | 1838.5 | 1831.3 | 1819.2 | 1773.0 | 1844.2 |
| 19 | 2107.6 | 2100.8 | 2089.2 | 2045.2 | 2113.0 |
| 20 | 2399.0 | 2392.5 | 2381.5 | 2339.4 | 2404.2 |
| 21 | 2713.4 | 2707.1 | 2696.6 | 2656.3 | 2718.3 |
| 22 | 3051.2 | 3045.2 | 3035.1 | 2996.4 | 3056.0 |
| 23 | 3413.2 | 3407.4 | 3397.7 | 3360.5 | 3417.8 |
| 24 | 3799.8 | 3794.2 | 3784.9 | 3749.1 | 3804.2 |
| 25 | 4211.6 | 4206.2 | 4197.2 | 4162.7 | 4215.8 |

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[1] Bole weight was calculated from ground level to given top diameter.

**Table 19 — Bole weight of bigleaf maple to top diameters outside bark and total bole weight, by diameter at breast height outside bark**[1]

| D.b.h. | Bole weight to a top diameter of (inches): | | | | Total bole |
|---|---|---|---|---|---|
| | 4 | 5 | 6 | 8 | |
| Inches | | | Ovendry pounds | | |
| 1 | 0 | 0 | 0 | 0 | 2.2 |
| 2 | 0 | 0 | 0 | 0 | 11.0 |
| 3 | 2.6 | 0 | 0 | 0 | 28.1 |
| 4 | 28.8 | 11.1 | 0 | 0 | 54.6 |
| 5 | 65.3 | 47.5 | 24.1 | 0 | 91.2 |
| 6 | 112.9 | 94.9 | 71.4 | 6.3 | 138.9 |
| 7 | 172.0 | 154.0 | 130.4 | 65.0 | 198.2 |
| 8 | 243.3 | 225.2 | 201.6 | 135.9 | 269.6 |
| 9 | 327.3 | 309.2 | 285.4 | 219.5 | 353.7 |
| 10 | 424.5 | 406.3 | 382.4 | 316.3 | 450.9 |
| 11 | 535.2 | 516.9 | 493.0 | 426.8 | 561.7 |
| 12 | 659.9 | 641.6 | 617.6 | 551.2 | 686.5 |
| 13 | 798.9 | 780.6 | 756.5 | 689.9 | 825.5 |
| 14 | 952.6 | 934.2 | 910.2 | 843.4 | 979.3 |
| 15 | 1121.4 | 1103.0 | 1078.8 | 1011.9 | 1148.1 |
| 16 | 1305.5 | 1287.0 | 1262.8 | 1195.8 | 1332.3 |
| 17 | 1505.2 | 1486.7 | 1462.5 | 1395.4 | 1532.1 |
| 18 | 1720.9 | 1702.4 | 1678.2 | 1610.9 | 1747.8 |
| 19 | 1952.9 | 1934.3 | 1910.0 | 1842.7 | 1979.8 |
| 20 | 2201.3 | 2182.7 | 2158.4 | 2091.0 | 2228.3 |
| 21 | 2466.5 | 2447.9 | 2423.5 | 2356.0 | 2493.5 |
| 22 | 2748.7 | 2730.1 | 2705.7 | 2638.1 | 2775.8 |
| 23 | 3048.2 | 3029.5 | 3005.1 | 2937.4 | 3075.2 |
| 24 | 3365.1 | 3346.4 | 3322.0 | 3254.2 | 3392.2 |
| 25 | 3699.8 | 3681.1 | 3656.6 | 3588.7 | 3726.9 |

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[1] Bole weight was calculated from ground level to given top diameter.

**Table 20 — Bole weight of Pacific madrone to top diameters outside bark and total bole weight, by diameter at breast height outside bark**[1]

| D.b.h. | Bole weight to a top diameter of (inches): | | | | Total bole |
|---|---|---|---|---|---|
| | 4 | 5 | 6 | 8 | |
| Inches | | | Ovendry pounds | | |
| 1 | 0 | 0 | 0 | 0 | 2.5 |
| 2 | 0 | 0 | 0 | 0 | 12.2 |
| 3 | 2.9 | 0 | 0 | 0 | 31.1 |
| 4 | 33.7 | 9.1 | 0 | 0 | 60.1 |
| 5 | 75.2 | 51.7 | 17.1 | 0 | 100.4 |
| 6 | 128.4 | 105.8 | 72.5 | 0 | 152.6 |
| 7 | 194.0 | 172.2 | 139.9 | 36.3 | 217.4 |
| 8 | 272.7 | 251.5 | 220.2 | 119.5 | 295.5 |
| 9 | 365.1 | 344.4 | 313.8 | 215.7 | 387.3 |
| 10 | 471.6 | 451.4 | 421.5 | 325.5 | 493.3 |
| 11 | 592.8 | 573.0 | 543.7 | 449.7 | 614.0 |
| 12 | 729.0 | 709.6 | 680.8 | 588.5 | 749.9 |
| 13 | 880.7 | 861.6 | 833.4 | 742.6 | 901.2 |
| 14 | 1048.3 | 1029.4 | 1001.7 | 912.4 | 1068.4 |
| 15 | 1232.0 | 1213.5 | 1186.1 | 1098.1 | 1251.9 |
| 16 | 1432.3 | 1414.1 | 1387.1 | 1300.3 | 1451.9 |
| 17 | 1649.5 | 1631.5 | 1604.8 | 1519.2 | 1668.9 |
| 18 | 1883.9 | 1866.1 | 1839.8 | 1755.2 | 1903.0 |
| 19 | 2135.7 | 2118.1 | 2092.1 | 2008.5 | 2154.6 |
| 20 | 2405.4 | 2387.9 | 2362.2 | 2279.5 | 2424.1 |
| 21 | 2693.0 | 2675.8 | 2650.3 | 2568.5 | 2711.5 |
| 22 | 2999.0 | 2981.9 | 2956.7 | 2875.7 | 3017.3 |
| 23 | 3323.5 | 3306.6 | 3281.6 | 3201.4 | 3341.6 |
| 24 | 3666.8 | 3650.1 | 3625.3 | 3545.8 | 3684.8 |
| 25 | 4029.2 | 4012.6 | 3988.1 | 3909.3 | 4047.0 |

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[1] Bole weight was calculated from ground level to given top diameter.

### Table 21 — Bole weight of tanoak to top diameters outside bark and total bole weight, by diameter at breast height outside bark[1]

| D.b.h. | Bole weight to a top diameter of (inches): 4 | 5 | 6 | 8 | Total bole |
|---|---|---|---|---|---|
| Inches | Ovendry pounds | | | | |
| 1 | 0 | 0 | 0 | 0 | 2.0 |
| 2 | 0 | 0 | 0 | 0 | 11.0 |
| 3 | 0 | 0 | 0 | 0 | 30.5 |
| 4 | 30.6 | 0 | 0 | 0 | 62.5 |
| 5 | 78.1 | 47.8 | 2.4 | 0 | 109.3 |
| 6 | 141.8 | 112.1 | 67.5 | 0 | 172.4 |
| 7 | 223.4 | 194.1 | 150.2 | 5.9 | 253.5 |
| 8 | 324.3 | 295.4 | 252.1 | 109.8 | 354.0 |
| 9 | 445.9 | 417.4 | 374.6 | 234.0 | 475.3 |
| 10 | 589.5 | 561.3 | 518.9 | 379.8 | 618.5 |
| 11 | 756.3 | 728.4 | 686.4 | 548.6 | 785.1 |
| 12 | 947.4 | 919.7 | 878.1 | 741.6 | 975.9 |
| 13 | 1163.9 | 1136.5 | 1095.2 | 959.8 | 1192.2 |
| 14 | 1406.9 | 1379.6 | 1338.7 | 1204.3 | 1435.0 |
| 15 | 1677.3 | 1650.3 | 1609.6 | 1476.2 | 1705.2 |
| 16 | 1976.2 | 1949.3 | 1909.0 | 1776.4 | 2003.9 |
| 17 | 2304.5 | 2277.8 | 2237.6 | 2105.9 | 2332.0 |
| 18 | 2663.0 | 2636.4 | 2596.5 | 2465.5 | 2690.4 |
| 19 | 3052.7 | 3026.3 | 2986.6 | 2856.3 | 3079.9 |
| 20 | 3474.4 | 3448.1 | 3408.7 | 3279.0 | 3501.5 |
| 21 | 3928.9 | 3902.8 | 3863.5 | 3734.6 | 3955.9 |
| 22 | 4417.2 | 4391.2 | 4352.1 | 4223.7 | 4444.0 |
| 23 | 4939.9 | 4914.0 | 4875.1 | 4747.3 | 4966.6 |
| 24 | 5497.8 | 5472.0 | 5433.3 | 5306.0 | 5524.4 |
| 25 | 6091.7 | 6066.0 | 6027.5 | 5900.8 | 6118.2 |

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1/ Bole weight was calculated from ground level to given top diameter.

### Table 22 — Total weight of residue for red alder with top bole diameters outside bark, by diameter at breast height outside bark[1]

| D.b.h | Residue weight <3 inches in diameter | Residue weight ≥3 inches in diameter above a top diameter of (inches): 4 | 5 | 6 | 8 |
|---|---|---|---|---|---|
| Inches | Ovendry pounds | | | | |
| 1 | 1.9 | 0 | 0 | 0 | 0 |
| 2 | 10.8 | 0 | 0 | 0 | 0 |
| 3 | 18.3 | 11.8 | 11.8 | 11.8 | 11.8 |
| 4 | 21.2 | 18.2 | 40.8 | 40.8 | 40.8 |
| 5 | 27.9 | 15.4 | 43.7 | 80.9 | 80.9 |
| 6 | 38.3 | 13.3 | 38.0 | 78.4 | 133.9 |
| 7 | 52.0 | 12.5 | 34.4 | 70.3 | 201.2 |
| 8 | 69.1 | 12.7 | 32.5 | 64.9 | 183.0 |
| 9 | 89.7 | 14.1 | 32.2 | 61.7 | 169.6 |
| 10 | 113.7 | 17.0 | 33.7 | 60.9 | 160.4 |
| 11 | 141.2 | 21.7 | 37.1 | 62.5 | 154.9 |
| 12 | 171.5 | 28.8 | 43.2 | 66.9 | 153.4 |
| 13 | 204.9 | 38.6 | 52.2 | 74.5 | 155.8 |
| 14 | 241.0 | 51.5 | 64.4 | 85.4 | 162.2 |
| 15 | 279.8 | 68.0 | 80.2 | 100.2 | 173.0 |
| 16 | 320.9 | 88.7 | 100.3 | 119.2 | 188.6 |
| 17 | 364.2 | 113.8 | 124.9 | 143.0 | 209.2 |
| 18 | 409.4 | 144.0 | 154.6 | 171.9 | 235.2 |
| 19 | 456.4 | 179.6 | 189.7 | 206.4 | 267.1 |
| 20 | 504.8 | 221.1 | 230.9 | 246.9 | 305.2 |
| 21 | 554.6 | 269.0 | 278.4 | 293.8 | 350.0 |
| 22 | 605.5 | 323.6 | 332.7 | 347.6 | 401.8 |
| 23 | 657.3 | 385.5 | 394.3 | 408.6 | 461.1 |
| 24 | 710.0 | 454.9 | 463.4 | 477.3 | 528.1 |
| 25 | 763.2 | 532.3 | 540.5 | 554.0 | 603.2 |

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1/ Residue includes all leaves, live and dead branchwood, and that part of the bole above a specific top diameter.

## Table 23 — Total weight of residue for giant chinkapin with top bole diameters outside bark, by diameter at breast height outside bark[1]

| D.b.h | Residue weight <3 inches in diameter | Residue weight ≥3 inches in diameter above a top diameter of (inches): | | | |
|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | |
| 1 | 1.8 | 0 | 0 | 0 | 0 |
| 2 | 10.0 | 0 | 0 | 0 | 0 |
| 3 | 16.6 | 10.5 | 10.5 | 10.5 | 10.5 |
| 4 | 20.7 | 14.1 | 34.2 | 34.2 | 34.2 |
| 5 | 28.0 | 11.6 | 33.9 | 67.1 | 67.1 |
| 6 | 38.3 | 9.8 | 28.8 | 61.0 | 110.8 |
| 7 | 51.4 | 8.7 | 25.2 | 53.3 | 160.3 |
| 8 | 67.1 | 8.0 | 22.7 | 47.7 | 142.7 |
| 9 | 85.6 | 8.0 | 21.2 | 43.6 | 129.2 |
| 10 | 106.6 | 8.5 | 20.6 | 41.0 | 118.9 |
| 11 | 130.2 | 9.6 | 20.7 | 39.5 | 111.1 |
| 12 | 156.6 | 11.3 | 21.6 | 39.0 | 105.2 |
| 13 | 185.6 | 13.7 | 23.3 | 39.5 | 101.2 |
| 14 | 217.2 | 16.8 | 25.8 | 40.9 | 98.7 |
| 15 | 251.5 | 20.8 | 29.2 | 43.4 | 97.8 |
| 16 | 288.3 | 25.6 | 33.5 | 46.9 | 98.3 |
| 17 | 327.8 | 31.3 | 38.8 | 51.6 | 100.2 |
| 18 | 369.8 | 38.0 | 45.2 | 57.3 | 103.5 |
| 19 | 414.4 | 45.9 | 52.7 | 64.3 | 108.3 |
| 20 | 461.5 | 54.9 | 61.4 | 72.5 | 114.6 |
| 21 | 511.1 | 65.2 | 71.4 | 82.0 | 122.3 |
| 22 | 563.1 | 76.8 | 82.8 | 92.9 | 131.6 |
| 23 | 617.6 | 89.8 | 95.5 | 105.3 | 142.5 |
| 24 | 674.5 | 104.3 | 109.8 | 119.2 | 155.0 |
| 25 | 733.7 | 120.3 | 125.6 | 134.7 | 169.2 |

[1] Residue includes all leaves, live and dead branchwood, and that part of the bole above a specific top diameter.

## Table 24 — Total weight of residue for bigleaf maple with top bole diameters outside bark, by diameter at breast height outside bark[1]

| D.b.h | Residue weight <3 inches in diameter | Residue weight ≥3 inches in diameter above a top diameter of (inches): | | | |
|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | |
| 1 | 3.2 | 0 | 0 | 0 | 0 |
| 2 | 15.4 | 0 | 0 | 0 | 0 |
| 3 | 23.5 | 12.5 | 15.1 | 15.1 | 15.1 |
| 4 | 32.8 | 12.6 | 30.4 | 41.5 | 41.5 |
| 5 | 44.9 | 13.0 | 30.8 | 54.2 | 78.3 |
| 6 | 58.2 | 15.4 | 33.3 | 56.8 | 121.9 |
| 7 | 73.1 | 19.6 | 37.6 | 61.2 | 126.6 |
| 8 | 89.1 | 26.0 | 44.1 | 67.8 | 133.4 |
| 9 | 106.2 | 34.9 | 53.1 | 76.9 | 142.8 |
| 10 | 124.0 | 46.8 | 65.0 | 88.9 | 155.0 |
| 11 | 142.4 | 61.8 | 80.1 | 104.0 | 170.3 |
| 12 | 161.2 | 80.2 | 98.5 | 122.5 | 188.9 |
| 13 | 180.3 | 102.1 | 120.5 | 144.5 | 211.1 |
| 14 | 199.6 | 127.7 | 146.1 | 170.2 | 236.9 |
| 15 | 219.1 | 157.0 | 175.5 | 199.6 | 266.5 |
| 16 | 238.7 | 190.3 | 208.7 | 232.9 | 299.9 |
| 17 | 258.5 | 227.5 | 245.9 | 270.2 | 337.3 |
| 18 | 278.3 | 268.6 | 287.2 | 311.4 | 378.7 |
| 19 | 298.3 | 313.9 | 332.4 | 356.7 | 424.1 |
| 20 | 318.4 | 363.2 | 381.8 | 406.1 | 473.5 |
| 21 | 338.6 | 416.6 | 435.2 | 459.6 | 527.1 |
| 22 | 359.0 | 474.2 | 492.9 | 517.3 | 584.9 |
| 23 | 379.5 | 536.0 | 554.6 | 579.1 | 646.8 |
| 24 | 400.2 | 601.9 | 620.6 | 645.1 | 712.9 |
| 25 | 421.1 | 672.1 | 690.8 | 715.3 | 783.1 |

[1] Residue includes all leaves, live and dead branchwood, and that part of the bole above a specific top diameter.

### Table 25 — Total weight of residue for Pacific madrone with top bole diameters outside bark, by diameter at breast height outside bark 1/

| D.b.h | Residue weight <3 inches in diameter | Residue weight ≥3 inches in diameter above a top diameter of (inches): | | | |
|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | |
| 1 | 3.0 | 0 | 0 | 0 | 0 |
| 2 | 15.2 | 0 | 0 | 0 | 0 |
| 3 | 20.1 | 16.1 | 19.0 | 19.0 | 19.0 |
| 4 | 27.7 | 15.1 | 39.7 | 48.8 | 48.8 |
| 5 | 38.3 | 15.3 | 38.8 | 73.5 | 90.5 |
| 6 | 51.5 | 17.2 | 39.8 | 73.1 | 145.6 |
| 7 | 67.3 | 21.2 | 43.0 | 75.2 | 178.9 |
| 8 | 85.4 | 27.7 | 48.9 | 80.2 | 180.9 |
| 9 | 105.5 | 37.4 | 58.1 | 88.7 | 186.8 |
| 10 | 127.4 | 50.8 | 71.1 | 100.9 | 196.9 |
| 11 | 150.7 | 68.4 | 88.2 | 117.5 | 211.5 |
| 12 | 175.4 | 90.7 | 110.1 | 138.8 | 231.1 |
| 13 | 201.2 | 118.0 | 137.1 | 165.3 | 256.0 |
| 14 | 227.9 | 150.7 | 169.5 | 197.3 | 286.6 |
| 15 | 255.4 | 189.3 | 207.9 | 235.2 | 323.2 |
| 16 | 283.5 | 234.1 | 252.4 | 279.4 | 366.1 |
| 17 | 312.2 | 285.4 | 303.4 | 330.1 | 415.7 |
| 18 | 341.4 | 343.5 | 361.3 | 387.6 | 472.2 |
| 19 | 370.9 | 408.6 | 426.2 | 452.2 | 535.8 |
| 20 | 400.7 | 481.1 | 498.5 | 524.3 | 607.0 |
| 21 | 430.6 | 561.2 | 578.5 | 603.9 | 685.8 |
| 22 | 460.7 | 649.2 | 666.3 | 691.5 | 772.5 |
| 23 | 490.9 | 745.3 | 762.2 | 787.1 | 867.4 |
| 24 | 521.1 | 849.7 | 866.4 | 891.2 | 970.7 |
| 25 | 551.2 | 962.6 | 979.2 | 1003.7 | 1082.5 |

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1/ Residue includes all leaves, live and dead branchwood, and that part of the bole above a specific top diameter.

### Table 26 — Total weight of residue for tanoak with top bole diameters outside bark, by diameter at breast height outside bark 1/

| D.b.h | Residue weight <3 inches in diameter | Residue weight ≥3 inches in diameter above a top diameter of (inches): | | | |
|---|---|---|---|---|---|
| | | 4 | 5 | 6 | 8 |
| Inches | Ovendry pounds | | | | |
| 1 | 2.8 | 0 | 0 | 0 | 0 |
| 2 | 14.9 | 0 | 0 | 0 | 0 |
| 3 | 23.4 | 16.7 | 16.7 | 16.7 | 16.7 |
| 4 | 31.8 | 18.6 | 49.2 | 49.2 | 49.2 |
| 5 | 43.7 | 18.2 | 48.4 | 93.9 | 96.3 |
| 6 | 59.1 | 17.8 | 47.5 | 92.2 | 159.6 |
| 7 | 78.2 | 17.6 | 46.8 | 90.7 | 235.0 |
| 8 | 101.1 | 17.3 | 46.2 | 89.5 | 231.8 |
| 9 | 128.1 | 17.1 | 45.6 | 88.5 | 229.1 |
| 10 | 159.1 | 17.0 | 45.2 | 87.6 | 226.7 |
| 11 | 194.3 | 16.9 | 44.8 | 86.8 | 224.5 |
| 12 | 233.8 | 16.8 | 44.5 | 86.1 | 222.6 |
| 13 | 277.7 | 16.8 | 44.2 | 85.4 | 220.9 |
| 14 | 326.2 | 16.7 | 44.0 | 84.9 | 219.3 |
| 15 | 379.2 | 16.8 | 43.8 | 84.4 | 217.9 |
| 16 | 436.8 | 16.8 | 43.7 | 84.0 | 216.6 |
| 17 | 499.3 | 16.9 | 43.6 | 83.7 | 215.5 |
| 18 | 566.5 | 17.0 | 43.5 | 83.4 | 214.4 |
| 19 | 638.6 | 17.1 | 43.5 | 83.2 | 213.5 |
| 20 | 715.7 | 17.3 | 43.6 | 83.1 | 212.7 |
| 21 | 797.9 | 17.6 | 43.7 | 83.0 | 211.9 |
| 22 | 885.1 | 17.8 | 43.8 | 82.9 | 211.3 |
| 23 | 977.5 | 18.1 | 44.0 | 82.9 | 210.7 |
| 24 | 1075.0 | 18.5 | 44.3 | 83.0 | 210.2 |
| 25 | 1177.9 | 18.9 | 44.5 | 83.1 | 209.8 |

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1/ Residue includes all leaves, live and dead branchwood, and that part of the bole above a specific top diameter.

Table 27 — Total weight of red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak trees by diameter at breast height outside bark [1/]

| D.b.h. | Red alder | Giant chinkapin | Bigleaf maple | Pacific madrone | Tanoak |
|---|---|---|---|---|---|
| Inches | | | Ovendry pounds | | |
| 1 | 1.9 | 1.8 | 3.2 | 3.0 | 2.8 |
| 2 | 10.8 | 10.0 | 15.4 | 15.2 | 14.9 |
| 3 | 30.0 | 27.1 | 38.7 | 39.2 | 40.1 |
| 4 | 62.0 | 54.9 | 74.3 | 76.6 | 81.1 |
| 5 | 108.8 | 95.2 | 123.2 | 128.8 | 139.9 |
| 6 | 172.2 | 149.1 | 186.4 | 197.1 | 218.7 |
| 7 | 254.1 | 218.0 | 264.6 | 282.5 | 319.1 |
| 8 | 355.8 | 303.0 | 358.5 | 385.8 | 442.7 |
| 9 | 479.0 | 405.2 | 468.5 | 508.0 | 591.1 |
| 10 | 624.8 | 525.5 | 595.3 | 649.8 | 765.6 |
| 11 | 794.6 | 665.0 | 739.4 | 811.9 | 967.4 |
| 12 | 989.7 | 824.4 | 901.3 | 995.0 | 1198.0 |
| 13 | 1211.2 | 1004.7 | 1081.3 | 1199.8 | 1458.4 |
| 14 | 1460.3 | 1206.6 | 1279.9 | 1426.9 | 1749.8 |
| 15 | 1738.1 | 1431.0 | 1497.5 | 1676.7 | 2073.2 |
| 16 | 2045.6 | 1678.6 | 1734.5 | 1950.0 | 2429.8 |
| 17 | 2383.8 | 1950.2 | 1991.2 | 2247.1 | 2820.6 |
| 18 | 2753.8 | 2246.4 | 2267.9 | 2568.7 | 3246.5 |
| 19 | 3156.5 | 2567.9 | 2565.1 | 2915.3 | 3708.5 |
| 20 | 3592.8 | 2915.4 | 2882.9 | 3287.1 | 4207.4 |
| 21 | 4063.8 | 3289.6 | 3221.8 | 3684.9 | 4744.4 |
| 22 | 4570.3 | 3691.1 | 3581.9 | 4108.9 | 5320.1 |
| 23 | 5113.1 | 4120.6 | 3963.6 | 4559.7 | 5935.4 |
| 24 | 5693.1 | 4578.5 | 4367.2 | 5037.6 | 6591.3 |
| 25 | 6311.3 | 5065.6 | 4792.9 | 5543.0 | 7288.5 |

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[1/] Tree weight includes leaves, live and dead branchwood, entire bole from ground to tip, and bark.

**Example**

To illustrate how to use these tables to estimate weights of potential residue, consider a clearcut of Pacific madrone and tanoak. All boles with d.b.h. of 10 inches and larger will be cut at a top diameter of 4 inches and removed from the site. All other trees will be felled and left. The number of trees per acre by species and d.b.h. for this example are shown in table 28. The total weight of aboveground biomass, residue, and 1,000-hour timelag fuels can be calculated from weights in tables 25, 26, and 27.

For example, to calculate the total weight of all Pacific madrone with d.b.h. of 10 inches, multiply the total weight per tree (table 27) by the number of trees (table 28):

649.8 lb × 30 trees per acre = 19,494 lb or 9.7 tons per acre.

The total residue from these trees will be that part of the bole less than 4 inches in diameter and all of the crown. Total residue can be determined from table 25 as the weight of residue less than 3 inches in d.o.b. (127.4 lb) plus the weight of crown and tip 3 to 4 inches in d.o.b. (50.8 lb):

Residue weight (127.4 + 50.8) lb per tree × 30 trees per acre
= 5,346 lb or 2.7 tons per acre.

The 1,000-hour timelag fuels for these 10-inch trees will include all of the crown greater than 3 inches in d.o.b. and that part of the tip that is 3 to 4 inches in d.o.b. because all bolewood greater than 4 inches in diameter will be harvested:

1,000-hour fuel weight (table 25) 50.8 lb × 30 trees per acre
= 1,527 lb or 0.76 ton per acre.

For trees less than 10 inches in d.b.h., 1,000-hour timelag fuels will include components of crown and bole that are 3 to 8 inches in d.o.b.

The total residue for the stand will include the residue from all trees greater than 10 inches in d.b.h. and the total weight of all trees less than 10 inches in d.b.h. because they will not be harvested.

Now suppose that all material less than 4 inches and greater than 1 inch in d.o.b. are to be chipped for fuel. The total weight of the material available for chips will include all crown and tip between 3 and 4 inches in d.o.b. (table 25) and all live crown, dead crown, and tip between 1 and 3 inches in d.o.b. (tables 10 and 15). For the 10-inch-d.b.h. Pacific madrone:

| | |
|---|---|
| Crown and tip 3-4 inches in d.o.b. (table 25) | 50.8 lb |
| Live crown 1-3 inches in d.o.b. (table 10) | 40.6 lb |
| Dead crown 1-3 inches in d.o.b. (table 10) | 4.4 lb |
| Tip 1-3 inches in d.o.b. (table 15) | 8.9 lb |
| Total weight per tree | 104.7 lb |

Total weight = 104.7 lb × 30 trees per acre = 3,141 lb or 1.6 tons per acre.

The weight of chippable material for the stand is listed in table 29.

Table 28 — Deriving weight of Pacific madrone and tanoak trees on a sample acre

| D.b.h. | Trees per acre | Total tree weight | Total residue weight | 1,000-h fuel weight (residue 3 to 6 inches in diameter) |
|---|---|---|---|---|
| Inches | Number | Ovendry tons per acre | | |
| | | PACIFIC MADRONE | | |
| 2 | 200 | 1.5 | 1.5 | 0 |
| 4 | 300 | 11.5 | 11.5 | 7.3 |
| 6 | 250 | 24.6 | 24.6 | 9.1 |
| 9 | 50 | 12.7 | 12.7 | 2.2 |
| 10 | 30 | 9.7 | 2.7 | .8 |
| 14 | 10 | 7.1 | 1.9 | .8 |
| Total | | 67.1 | 54.9 | 20.2 |
| | | TANOAK | | |
| 2 | 100 | 0.7 | 0.7 | 0 |
| 4 | 50 | 2.0 | 2.0 | 1.2 |
| 6 | 100 | 10.9 | 10.9 | 4.6 |
| 9 | 25 | 7.4 | 7.4 | 1.1 |
| 10 | 15 | 5.7 | 1.3 | .1 |
| 14 | 5 | 4.4 | .9 | .04 |
| Total | | 31.2 | 23.2 | 7.0 |
| All trees | | 98.3 | 78.1 | 27.2 |

Table 29 — Chippable material from Pacific madrone and tanoak trees on a sample acre

| D.b.h. | Trees per acre | Total residue weight | Total weight of residue 1 to 4 inches in diameter |
|---|---|---|---|
| Inches | Number | -------- Ovendry tons per acre | ------- |
| | | PACIFIC MADRONE | |
| 2 | 200 | 1.5 | 1.2 |
| 4 | 300 | 11.5 | 4.3 |
| 6 | 250 | 24.6 | 4.6 |
| 9 | 50 | 12.7 | 2.0 |
| 10 | 30 | 2.7 | 1.6 |
| 14 | 10 | 1.9 | 1.3 |
| Total | | 54.9 | 15.0 |
| | | TANOAK | |
| 2 | 100 | .7 | .5 |
| 4 | 50 | 2.0 | .8 |
| 6 | 100 | 10.9 | 2.0 |
| 9 | 25 | 7.4 | .8 |
| 10 | 15 | 1.3 | .6 |
| 14 | 5 | .9 | .4 |
| Total | | 23.2 | 5.1 |
| All trees | | 78.1 | 20.1 |

# Appendix 2. Summary Tables of Data Used in Developing Equations in Tables 1 to 6

## Table 30 — Data from red alder sampled

| D.b.h. | Tree height | Age | Crown length | Crown width | Diameter of bole at base of crown | Dead crown weight | | | | | Live crown weight | | | | | | Bole volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Branchwood diameter (inches) | | | | Total dead | Foliage | Branchwood diameter (inches) | | | | Total live | |
| | | | | | | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | |
| Inches | Feet | Years | Feet | Feet | Inches | Pounds | | | | | | | | | | | Cubic feet |
| 1.0 | 15.1 | 6 | 6.9 | 5.1 | 0.8 | 0 | 0 | 0 | 0 | 0.1 | 0.2 | 0.3 | 0.2 | 0 | 0 | 0.7 | 0.1 |
| 1.1 | 17.1 | 5 | 6.6 | 6.7 | .7 | 0 | 0 | 0 | 0 | 0 | .2 | .2 | .1 | 0 | 0 | .5 | .1 |
| 1.3 | 15.8 | 9 | 9.2 | 5.1 | 1.0 | 0 | 0 | 0 | 0 | 0 | .3 | .4 | .4 | 0 | 0 | 1.1 | .1 |
| 2.2 | 42.6 | 9 | 27.4 | 10.7 | 1.6 | .1 | .1 | 0 | 0 | .2 | .7 | .8 | 1.0 | 0 | 0 | 2.4 | .5 |
| 2.4 | 24.8 | 6 | 18.2 | 10.7 | 2.3 | .1 | 0 | 0 | 0 | .2 | 1.7 | 2.0 | 2.5 | 0 | 0 | 6.2 | .5 |
| 2.4 | 28.5 | 12 | 11.3 | 6.7 | 1.6 | .1 | 0 | 0 | 0 | .1 | .4 | .5 | .6 | 0 | 0 | 1.5 | .6 |
| 2.5 | 22.3 | 14 | 9.2 | 5.2 | 1.5 | .1 | .7 | 0 | 0 | .9 | .6 | .7 | .9 | 0 | 0 | 2.1 | .3 |
| 2.9 | 24.7 | 18 | 11.1 | 8.0 | 1.8 | .1 | .4 | 0 | 0 | .5 | 1.4 | 1.6 | 2.2 | 0 | 0 | 5.1 | .6 |
| 3.3 | 27.9 | 17 | 14.1 | 11.5 | 2.3 | .1 | 0 | 0 | 0 | .1 | 1.6 | 1.8 | 2.5 | 0 | 0 | 5.9 | .8 |
| 3.5 | 45.1 | 14 | 8.9 | 5.9 | 1.0 | .1 | .7 | 0 | 0 | .8 | .3 | .3 | .3 | 0 | 0 | .8 | 1.4 |
| 3.5 | 57.5 | 12 | 11.2 | 8.1 | 1.5 | .1 | 0 | 0 | 0 | .1 | 1.3 | 1.5 | 1.5 | 0 | 0 | 4.4 | 1.8 |
| 4.2 | 43.6 | 10 | 18.5 | 11.4 | 2.6 | .7 | 2.4 | 0 | 0 | 3.1 | 2.3 | 2.6 | 4.0 | 2.0 | 0 | 10.9 | 2.0 |
| 4.5 | 44.6 | 19 | 19.2 | 9.7 | 3.0 | .2 | .1 | 0 | 0 | .3 | 2.4 | 2.7 | 3.9 | 0 | 0 | 9.0 | 2.6 |
| 4.7 | 36.6 | 22 | 16.6 | 10.3 | 3.3 | .1 | .3 | .2 | 0 | .6 | 3.1 | 3.4 | 5.6 | 6.1 | 0 | 18.2 | 2.3 |
| 4.8 | 30.9 | 7 | 30.9 | 15.3 | 6.9 | .2 | .3 | 0 | 0 | .5 | 7.0 | 7.7 | 12.4 | 9.5 | 0 | 36.5 | 1.7 |
| 5.0 | 46.0 | 11 | 27.6 | 15.7 | 3.8 | .2 | .7 | 0 | 0 | .9 | 3.8 | 4.2 | 6.5 | 3.3 | 0 | 17.8 | 3.1 |
| 5.8 | 43.7 | 27 | 21.9 | 11.8 | 3.8 | .3 | .3 | 0 | 0 | .6 | 3.7 | 4.1 | 5.9 | .7 | 0 | 14.4 | 3.5 |
| 6.4 | 80.4 | 22 | 37.2 | 15.6 | 4.7 | .3 | 5.4 | .6 | 0 | 6.3 | 5.1 | 5.6 | 9.0 | 9.7 | 0 | 29.3 | 7.7 |
| 6.5 | 72.1 | 34 | 22.9 | 8.6 | 3.8 | 0 | 0 | 0 | 0 | 0 | 3.0 | 3.3 | 5.6 | 6.2 | 0 | 18.0 | 7.4 |
| 6.8 | 73.4 | 22 | 8.0 | 11.5 | 2.5 | .1 | 1.8 | 1.3 | 0 | 3.3 | 1.4 | 1.5 | 2.5 | 2.7 | 0 | 8.1 | 8.8 |
| 7.1 | 52.9 | 17 | 27.4 | 16.4 | 4.7 | .4 | 1.7 | 0 | 0 | 2.1 | 6.6 | 7.2 | 12.4 | 13.9 | 0 | 40.0 | 6.5 |
| 7.7 | 64.0 | 28 | 29.9 | 20.8 | 4.9 | 0 | 0 | 0 | 0 | 0 | 5.1 | 5.5 | 9.5 | 12.6 | 0 | 32.8 | 10.6 |
| 8.1 | 52.4 | 16 | 34.5 | 21.8 | 6.5 | .8 | 2.5 | 0 | 0 | 3.3 | 9.0 | 9.8 | 17.0 | 20.0 | 0 | 55.9 | 8.0 |
| 8.6 | 45.4 | 33 | 28.2 | 16.4 | 7.3 | .8 | 5.2 | 3.1 | 2.3 | 11.4 | 9.2 | 10.0 | 18.9 | 28.0 | 0 | 66.2 | 7.8 |
| 9.2 | 72.3 | 59 | 33.2 | 13.1 | 7.2 | .3 | 1.3 | 0 | 0 | 1.6 | 11.1 | 11.9 | 24.8 | 41.9 | 3.5 | 93.1 | 14.5 |
| 9.5 | 87.7 | 40 | 37.1 | 18.9 | 6.2 | .2 | 1.2 | 1.3 | 0 | 2.7 | 7.8 | 8.6 | 14.4 | 17.4 | 0 | 48.2 | 18.1 |
| 9.7 | 66.1 | 36 | 45.7 | 23.0 | 7.5 | .7 | 2.8 | .1 | 0 | 3.7 | 11.3 | 12.3 | 22.9 | 34.6 | 0 | 81.1 | 12.5 |
| 10.2 | 95.0 | 52 | 35.6 | 16.2 | 6.5 | .2 | .1 | 0 | 0 | .3 | 8.4 | 9.1 | 18.7 | 31.2 | 8.9 | 76.3 | 26.4 |
| 10.3 | 73.7 | 31 | 52.2 | 21.1 | 7.2 | .6 | 54.3 | 12.7 | 0 | 67.6 | 15.0 | 16.1 | 34.3 | 57.2 | 26.7 | 149.4 | 18.4 |
| 11.5 | 91.7 | 50 | 60.7 | 14.7 | 6.7 | .9 | 3.4 | 50.4 | .6 | 55.4 | 10.6 | 11.4 | 23.6 | 39.1 | 0 | 84.8 | 45.1 |
| 11.6 | 80.9 | 45 | 47.1 | 28.1 | 8.9 | .2 | .1 | 2.2 | 0 | 2.4 | 14.1 | 15.0 | 33.9 | 59.4 | 31.9 | 154.4 | 26.6 |
| 11.7 | 70.4 | 30 | 36.4 | 24.6 | 8.6 | .8 | 13.1 | 23.0 | 0 | 36.9 | 21.4 | 23.0 | 46.8 | 81.2 | 3.5 | 175.9 | 22.6 |
| 12.1 | 65.9 | 53 | 36.2 | 25.5 | 9.8 | 2.1 | 3.6 | 3.9 | 0 | 9.5 | 20.5 | 21.9 | 47.0 | 80.2 | 4.0 | 173.6 | 24.4 |
| 12.3 | 88.3 | 28 | 40.8 | 25.4 | 8.6 | 0.2 | 5.3 | 15.5 | 0 | 21.0 | 15.8 | 17.1 | 32.8 | 52.0 | 0 | 117.7 | 34.4 |
| 12.6 | 88.5 | 89 | 47.8 | 22.2 | 9.2 | .4 | 2.3 | 9.8 | 0 | 12.6 | 14.6 | 15.5 | 34.6 | 61.9 | 21.5 | 148.1 | 40.5 |
| 12.6 | 65.3 | 22 | 44.7 | 31.5 | 11.3 | 2.8 | 13.6 | 33.3 | 0 | 49.7 | 27.3 | 29.0 | 64.3 | 117.0 | 14.1 | 251.7 | 19.7 |
| 12.7 | 86.0 | 38 | 30.8 | 22.8 | 8.0 | .3 | 3.9 | 26.6 | 0 | 30.8 | 19.2 | 20.7 | 42.4 | 72.7 | 14.3 | 169.3 | 33.0 |
| 13.3 | 75.8 | 30 | 32.0 | 28.7 | 8.8 | 1.2 | 24.5 | 28.4 | 0 | 54.1 | 21.1 | 22.7 | 44.6 | 75.3 | 0 | 163.6 | 29.3 |
| 13.7 | 85.2 | 35 | 55.2 | 30.1 | 10.7 | .2 | 4.3 | 12.3 | 0 | 16.8 | 23.4 | 25.1 | 52.0 | 89.4 | 3.0 | 192.8 | 34.9 |
| 14.2 | 74.6 | 52 | 40.5 | 24.6 | 10.5 | 1.1 | 4.9 | 18.0 | 1.9 | 25.8 | 26.5 | 28.2 | 63.4 | 106.3 | 53.2 | 277.7 | 33.1 |
| 14.5 | 84.7 | 95 | 29.6 | 23.8 | 7.8 | 2.9 | 6.2 | 8.3 | 0 | 17.4 | 13.6 | 14.4 | 33.9 | 58.2 | 51.2 | 171.5 | 35.5 |
| 15.1 | 91.0 | 46 | 62.8 | 24.0 | 12.5 | .5 | 1.9 | .5 | 0 | 2.9 | 21.0 | 22.0 | 56.1 | 103.8 | 111.9 | 314.8 | 58.4 |
| 16.3 | 95.6 | 61 | 42.5 | 37.8 | 11.9 | 2.5 | 3.7 | 11.2 | 0 | 17.3 | 29.1 | 30.8 | 74.0 | 135.5 | 118.8 | 388.2 | 95.6 |
| 16.6 | 95.5 | 46 | 70.9 | 39.9 | 14.6 | .5 | 5.8 | 23.4 | 1.6 | 31.3 | 42.6 | 44.4 | 119.2 | 224.3 | 370.9 | 801.4 | 61.8 |
| 17.0 | 96.3 | 45 | 55.7 | 32.3 | 12.9 | 1.2 | 14.2 | 55.4 | 0 | 70.8 | 45.2 | 47.9 | 108.7 | 195.6 | 43.4 | 440.9 | 63.1 |
| 18.0 | 77.7 | 40 | 49.4 | 32.5 | 14.2 | .6 | 7.9 | 30.3 | 0 | 38.8 | 51.9 | 54.7 | 132.3 | 243.5 | 143.3 | 625.8 | 58.6 |
| 18.7 | 95.0 | 52 | 43.9 | 28.8 | 10.7 | 2.1 | 4.0 | 36.2 | 7.7 | 50.0 | 26.3 | 27.9 | 63.2 | 112.3 | 46.1 | 275.8 | 99.8 |
| 19.7 | 82.0 | 35 | 41.3 | 36.2 | 12.8 | 1.4 | 21.1 | 108.9 | 10.5 | 141.9 | 63.4 | 66.8 | 162.1 | 301.1 | 136.4 | 729.8 | 73.8 |
| 20.2 | 95.3 | 56 | 36.1 | 29.7 | 13.5 | .2 | .3 | 0 | 0 | .5 | 31.2 | 32.9 | 78.8 | 143.9 | 74.8 | 361.5 | 110.4 |
| 21.9 | 103.1 | 69 | 41.9 | 47.8 | 15.9 | .9 | 6.9 | 7.6 | 0 | 15.4 | 64.4 | 67.1 | 181.4 | 346.7 | 447.8 | 1107.3 | 132.7 |
| 22.1 | 83.8 | 48 | 47.7 | 35.4 | 15.1 | 1.0 | 9.4 | 76.7 | 18.2 | 105.3 | 68.2 | 71.5 | 180.7 | 340.6 | 216.2 | 877.2 | 78.4 |
| 24.1 | 110.5 | 80 | 40.0 | 29.5 | 13.7 | 4.5 | 5.3 | 13.3 | 55.7 | 78.7 | 56.1 | 58.8 | 150.7 | 283.4 | 258.2 | 807.2 | 155.3 |
| 24.8 | 72.1 | 46 | 55.3 | 49.0 | 23.9 | 2.4 | 24.6 | 9.9 | 54.8 | 91.7 | 144.2 | 149.7 | 410.3 | 792.2 | 982.0 | 2478.4 | 97.7 |

## Table 31 — Data from giant chinkapin sampled

| D.b.h. | Tree height | Age | Crown length | Crown width | Diameter of bole at base of crown | Dead crown weight | | | | | Live crown weight | | | | | | Bole volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Branchwood diameter (inches) | | | | Total dead | | Branchwood diameter (inches) | | | | Total live | |
| | | | | | | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | Foliage | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | |
| Inches | Feet | Years | Feet | Feet | Inches | Pounds | | | | | | | | | | | Cubic feet |
| 1.3 | 11.5 | 20 | 7.2 | 3.9 | 1.5 | 0 | 0 | 0 | 0 | 0 | .8 | .5 | .5 | 0 | 0 | 1.8 | 0.1 |
| 1.4 | 11.2 | 53 | 4.2 | 5.9 | .9 | .2 | .4 | 0 | 0 | .6 | .6 | .4 | .6 | 0 | 0 | 1.7 | .1 |
| 1.6 | 14.9 | 32 | 8.7 | 6.9 | 1.3 | .1 | 0 | 0 | 0 | .1 | .8 | .5 | .6 | 0 | 0 | 1.9 | .1 |
| 2.0 | 17.5 | 18 | 12.9 | 7.4 | 2.0 | .3 | .4 | 0 | 0 | .7 | .7 | .4 | .6 | 0 | 0 | 1.7 | .2 |
| 2.9 | 25.9 | 60 | 6.4 | 5.8 | 1.1 | 1.3 | 3.4 | 0 | 0 | 4.8 | 1.0 | .7 | .9 | 0 | 0 | 2.5 | .7 |
| 3.0 | 21.4 | 30 | 9.2 | 6.8 | 1.7 | .3 | .6 | 0 | 0 | .8 | .6 | .4 | .4 | 0 | 0 | 1.3 | .5 |
| 3.7 | 37.9 | 45 | 23.1 | 7.0 | 3.0 | 1.3 | 2.7 | 0 | 0 | 4.0 | 2.6 | 1.8 | 2.7 | 0 | 0 | 7.1 | 1.2 |
| 4.2 | 25.0 | 75 | 13.8 | 6.8 | 3.3 | .5 | 1.0 | 0 | 0 | 1.6 | 4.1 | 2.8 | 4.7 | 1.6 | 0 | 13.3 | 1.2 |
| 5.0 | 26.9 | 63 | 13.1 | 9.4 | 4.1 | 3.0 | 8.0 | .9 | 0 | 11.9 | 5.6 | 3.9 | 6.7 | 4.2 | 0 | 20.3 | 2.1 |
| 5.1 | 35.9 | 74 | 22.4 | 7.9 | 3.7 | .9 | 1.1 | 0 | 0 | 2.1 | 4.4 | 3.0 | 4.3 | 0 | 0 | 11.7 | 2.1 |
| 5.6 | 43.9 | 64 | 20.5 | 8.3 | 4.0 | 1.7 | 5.8 | .8 | 0 | 8.3 | 6.2 | 4.3 | 7.4 | 3.9 | 0 | 21.8 | 3.2 |
| 6.2 | 52.4 | 91 | 25.5 | 12.3 | 4.8 | .7 | 3.7 | .1 | 0 | 4.6 | 5.1 | 3.5 | 6.1 | 2.9 | 0 | 17.6 | 5.2 |
| 6.8 | 53.4 | 49 | 50.0 | 10.6 | 4.4 | 4.0 | 10.9 | 2.3 | 0 | 17.2 | 9.5 | 6.6 | 11.5 | 6.0 | 0 | 33.6 | 5.8 |
| 6.9 | 45.1 | 63 | 29.6 | 9.4 | 5.9 | 4.6 | 12.4 | 1.1 | 0 | 18.0 | 8.6 | 6.1 | 10.9 | 8.1 | 0 | 33.7 | 4.9 |
| 7.6 | 52.7 | 75 | 20.0 | 13.7 | 4.5 | 4.6 | 12.6 | 0 | 0 | 17.2 | 8.6 | 6.0 | 10.6 | 6.5 | 0 | 31.8 | 6.8 |
| 7.7 | 39.2 | 71 | 13.1 | 10.8 | 4.0 | 5.6 | 18.5 | 3.5 | 0 | 27.6 | 7.1 | 5.0 | 8.6 | 4.8 | 0 | 25.5 | 5.4 |
| 8.2 | 55.0 | 68 | 29.5 | 12.2 | 6.0 | 4.0 | 16.3 | 0 | 0 | 20.4 | 13.3 | 9.5 | 17.9 | 17.6 | 0 | 58.3 | 8.7 |
| 8.7 | 46.6 | 55 | 27.6 | 11.5 | 6.9 | 13.4 | 8.2 | 6.2 | 0 | 27.8 | 17.8 | 12.7 | 23.6 | 19.7 | 0 | 73.9 | 8.2 |
| 9.2 | 64.5 | 56 | 32.0 | 13.9 | 6.8 | 5.6 | 7.6 | 15.9 | 0 | 29.1 | 18.3 | 13.0 | 24.4 | 21.5 | 0 | 77.3 | 14.7 |
| 9.7 | 51.6 | 83 | 28.7 | 11.8 | 6.9 | .9 | 6.4 | 6.5 | 0 | 13.8 | 12.6 | 9.1 | 17.8 | 18.2 | 0 | 57.8 | 13.0 |
| 10.2 | 57.0 | 102 | 37.7 | 14.3 | 8.5 | 4.2 | 8.6 | 7.8 | 0 | 20.6 | 21.3 | 15.4 | 30.7 | 33.3 | 0 | 100.8 | 16.5 |
| 11.2 | 54.0 | 89 | 24.5 | 14.8 | 7.2 | 6.4 | 15.1 | 11.5 | 0 | 33.0 | 15.4 | 11.0 | 20.7 | 19.6 | 0 | 66.7 | 16.5 |
| 11.6 | 52.6 | 109 | 30.0 | 13.8 | 8.3 | 2.8 | 6.8 | 4.1 | 0 | 13.7 | 22.9 | 16.6 | 34.0 | 40.0 | 15.9 | 129.3 | 21.6 |
| 12.6 | 73.4 | 123 | 37.6 | 14.0 | 8.5 | 3.0 | 21.9 | 3.0 | 0 | 27.9 | 25.9 | 18.7 | 36.8 | 37.0 | 0 | 118.3 | 31.6 |
| 14.4 | 59.2 | 75 | 39.6 | 19.3 | 11.7 | 9.0 | 17.2 | 10.4 | 0 | 36.6 | 41.9 | 30.8 | 64.6 | 78.6 | 11.4 | 227.3 | 33.9 |
| 14.6 | 72.7 | 195 | 37.0 | 17.8 | 9.0 | 3.6 | 11.5 | 19.6 | 0 | 34.7 | 23.1 | 17.3 | 39.2 | 54.4 | 14.4 | 148.5 | 33.4 |
| 18.0 | 66.7 | 150 | 24.3 | 21.2 | 9.9 | 14.2 | 16.8 | 34.2 | 25.7 | 90.9 | 54.9 | 41.0 | 91.9 | 127.3 | 37.5 | 352.6 | 57.9 |
| 19.9 | 80.2 | 179 | 31.0 | 19.5 | 10.8 | 5.2 | 16.9 | 41.0 | 0 | 63.1 | 54.1 | 39.8 | 85.0 | 106.7 | 12.5 | 298.0 | 72.6 |
| 22.0 | 67.6 | 98 | 38.7 | 21.1 | 14.5 | 15.4 | 36.4 | 58.4 | 109.4 | 219.6 | 44.6 | 33.0 | 72.1 | 94.0 | 19.8 | 263.5 | 65.9 |
| 23.6 | 86.6 | 185 | 52.3 | 23.6 | 18.2 | 6.5 | 30.3 | 35.7 | 0 | 72.5 | 127.2 | 95.8 | 221.2 | 320.6 | 99.1 | 863.8 | 98.0 |

## Table 32 — Data from bigleaf maple sampled

| D.b.h. | Tree height | Age | Crown length | Crown width | Diameter of bole at base of crown | Dead crown weight | | | | | Live crown weight | | | | | | Bole volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Branchwood diameter (inches) | | | | Total dead | | Branchwood diameter (inches) | | | | Total live | |
| | | | | | | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | Foliage | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ | | |
| Inches | Feet | Years | Feet | Feet | Inches | Pounds | | | | | | | | | | | Cubic feet |
| 1.6 | 18.1 | 12 | 14.4 | 9.7 | 1.6 | 0.1 | 0 | 0 | 0 | 0.1 | 0.7 | 0.3 | 2.6 | 0 | 0 | 3.6 | .2 |
| 4.0 | 39.7 | 31 | 53.8 | 16.4 | 3.0 | .5 | .5 | 0 | 0 | 1.0 | 1.7 | .7 | 6.8 | .7 | 0 | 9.9 | 1.5 |
| 5.2 | 52.0 | 31 | 30.4 | 18.9 | 2.8 | .2 | 1.5 | 1.0 | 0 | 2.7 | 2.5 | 1.0 | 9.9 | 12.7 | 4.1 | 30.3 | 3.5 |
| 5.2 | 58.8 | 18 | 26.8 | 10.9 | 2.7 | .1 | 3.6 | 2.7 | 0 | 6.4 | 1.7 | .7 | 6.7 | 7.0 | 0 | 16.1 | 3.5 |
| 5.7 | 65.9 | 45 | 39.3 | 23.5 | 4.0 | .2 | .8 | 0 | 0 | 1.0 | 2.5 | 1.0 | 9.6 | 2.5 | 0 | 15.6 | 4.6 |
| 6.2 | 58.5 | 29 | 37.6 | 15.3 | 4.0 | .4 | 3.2 | 1.3 | 0 | 4.9 | 2.2 | .9 | 8.7 | 7.8 | 0 | 19.6 | 3.8 |
| 6.3 | 51.9 | 29 | 34.1 | 21.1 | 4.8 | .2 | .8 | 0 | 0 | 1.0 | 4.3 | 1.7 | 16.8 | 15.3 | 0 | 38.2 | 5.0 |
| 7.0 | 75.2 | 30 | 55.5 | 26.2 | 5.4 | .1 | 1.7 | 1.4 | 0 | 3.2 | 5.0 | 2.0 | 20.1 | 18.2 | 0 | 45.4 | 7.3 |
| 8.4 | 76.0 | 32 | 50.2 | 12.5 | 6.7 | .3 | 1.9 | 1.4 | 0 | 3.6 | 3.5 | 1.4 | 13.5 | 24.3 | 17.5 | 60.1 | 10.0 |
| 9.4 | 48.9 | 31 | 31.2 | 29.8 | 7.5 | .8 | 7.0 | 7.7 | 0 | 15.5 | 10.0 | 3.8 | 38.4 | 94.8 | 76.4 | 223.4 | 9.7 |
| 11.7 | 69.8 | 45 | 33.2 | 21.2 | 6.3 | .5 | 7.1 | 5.3 | 0 | 12.9 | 6.7 | 2.6 | 25.2 | 52.0 | 26.7 | 113.2 | 18.3 |
| 12.0 | 55.8 | 37 | 34.1 | 29.7 | 9.8 | 1.5 | 18.9 | 27.2 | 14.6 | 62.2 | 12.6 | 4.8 | 47.2 | 134.9 | 185.8 | 385.2 | 15.2 |
| 13.0 | 63.4 | 37 | 37.6 | 25.5 | 10.5 | 1.5 | 11.5 | 32.1 | 0 | 45.1 | 9.6 | 3.7 | 36.5 | 84.8 | 57.9 | 192.4 | 20.6 |
| 14.6 | 96.0 | 64 | 68.4 | 24.6 | 11.7 | .6 | 10.4 | 20.8 | 0 | 31.8 | 9.3 | 3.6 | 35.2 | 88.3 | 81.9 | 218.3 | 45.1 |
| 15.6 | 79.3 | 38 | 66.5 | 33.0 | 11.5 | 1.3 | 28.5 | 31.7 | 2.6 | 64.0 | 17.6 | 6.6 | 65.8 | 220.6 | 366.3 | 676.9 | 23.4 |
| 17.3 | 107.5 | 114 | 51.7 | 28.1 | 9.8 | .3 | 3.9 | 4.3 | 0 | 8.4 | 12.2 | 4.6 | 46.2 | 135.9 | 194.4 | 393.3 | 53.7 |

## Table 33 — Data from Pacific madrone sampled

| D.b.h. | Tree height | Age | Crown length | Crown width | Diameter of bole at base of crown | Dead crown weight |  |  |  |  | Live crown weight |  |  |  |  |  | Bole volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Branchwood diameter (inches) |  |  |  | Total dead |  | Branchwood diameter (inches) |  |  |  | Total live |  |
|  |  |  |  |  |  | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ |  | Foliage | 0-0.24 | 0.25-0.99 | 1-2.99 | 3+ |  |  |
| Inches | Feet | Years | Feet | Feet | Inches | Pounds |  |  |  |  |  |  |  |  |  |  | Cubic feet |
| 1.2 | 11.4 | 32 | 5.9 | 3.8 | 1.3 | 0.1 | 0.1 | 0 | 0 | 0.2 | 2.7 | 1.8 | 3.4 | 0 | 0 | 7.8 | 0.1 |
| 1.3 | 19.7 | 31 | 6.9 | 2.8 | 0.9 | .1 | 0 | 0 | 0 | .1 | 0.3 | 0.2 | 0 | 0 | 0 | 0.5 | .3 |
| 2.1 | 23.0 | 48 | 13.3 | 5.6 | 2.0 | .3 | .7 | 0 | 0 | 1.0 | .8 | .5 | 1.4 | .7 | 0 | 3.5 | .5 |
| 2.7 | 22.9 | 103 | 9.3 | 4.6 | 1.9 | .5 | .5 | 0 | 0 | 1.0 | 1.1 | .7 | 1.8 | 1.2 | 0 | 4.7 | .7 |
| 2.7 | 22.1 | 71 | 13.9 | 5.1 | 2.3 | .3 | .9 | 0 | 0 | 1.2 | 1.6 | 1.0 | 1.9 | 0 | 0 | 4.5 | .5 |
| 3.1 | 17.8 | 38 | 6.2 | 3.4 | 1.6 | .2 | .3 | 0 | 0 | .5 | .4 | .3 | 0.3 | 0 | 0 | .9 | .4 |
| 4.2 | 25.2 | 66 | 12.0 | 11.5 | 3.4 | 0.8 | 4.9 | 0 | 0 | 5.7 | 2.7 | 1.6 | 5.7 | 5.6 | 0 | 15.5 | 1.6 |
| 4.2 | 24.4 | 51 | 16.2 | 7.7 | 3.4 | .3 | .6 | 0 | 0 | .9 | 3.6 | 2.2 | 6.7 | 5.7 | 0 | 18.3 | 1.2 |
| 4.4 | 24.8 | 69 | 15.3 | 7.7 | 3.8 | 1.2 | 3.2 | .4 | 0 | 4.8 | 4.2 | 2.6 | 7.6 | 5.8 | 0 | 20.1 | 1.8 |
| 5.2 | 26.9 | 107 | 15.9 | 8.4 | 4.0 | 1.0 | 3.1 | .4 | 0 | 4.4 | 4.2 | 2.6 | 7.6 | 5.8 | 0 | 20.3 | 2.0 |
| 5.4 | 32.0 | 76 | 24.6 | 6.0 | 5.0 | .4 | .7 | 0 | 0 | 1.1 | 7.1 | 4.4 | 13.2 | 3.4 | 0 | 28.1 | 2.8 |
| 5.8 | 29.5 | 173 | 22.6 | 5.9 | 5.3 | .7 | .8 | 0 | 0 | 1.5 | 6.9 | 4.3 | 12.9 | 5.5 | 0 | 29.7 | 2.7 |
| 6.2 | 41.0 | 63 | 22.1 | 8.9 | 4.3 | 1.8 | 4.4 | .2 | 0 | 6.4 | 5.9 | 3.6 | 11.2 | 5.4 | 0 | 26.1 | 4.0 |
| 7.2 | 55.0 | 80 | 41.2 | 11.2 | 6.2 | 1.0 | 5.7 | 4.5 | 0 | 11.1 | 11.0 | 6.4 | 25.2 | 32.1 | 7.0 | 81.7 | 7.2 |
| 7.4 | 57.3 | 69 | 18.6 | 8.2 | 3.7 | .1 | .7 | 4.2 | 0 | 4.9 | 2.3 | 1.3 | 4.7 | 4.4 | 0 | 12.7 | 6.4 |
| 7.8 | 36.9 | 102 | 20.8 | 12.1 | 4.6 | 2.1 | 5.8 | 0 | 0 | 7.9 | 8.9 | 4.9 | 24.5 | 37.6 | 69.8 | 145.6 | 4.6 |
| 8.3 | 59.2 | 191 | 30.0 | 11.5 | 5.9 | 4.9 | 10.1 | 3.4 | 0 | 18.4 | 13.6 | 8.0 | 29.3 | 33.8 | 0 | 84.7 | 10.2 |
| 9.0 | 34.9 | 95 | 27.7 | 10.5 | 7.5 | 1.5 | 2.5 | 1.0 | 0 | 4.9 | 7.2 | 4.1 | 17.3 | 23.5 | 18.8 | 70.9 | 6.9 |
| 9.2 | 35.9 | 175 | 13.2 | 13.6 | 5.0 | 3.0 | 16.3 | 4.9 | 0 | 24.2 | 13.1 | 7.3 | 34.3 | 52.0 | 68.2 | 175.0 | 8.0 |
| 10.3 | 33.9 | 81 | 16.0 | 14.2 | 7.6 | 2.5 | 22.4 | 9.2 | 0 | 34.0 | 12.5 | 6.9 | 33.3 | 54.4 | 53.9 | 161.0 | 10.8 |
| 10.7 | 64.4 | 193 | 40.1 | 13.1 | 7.0 | 8.7 | 35.4 | 13.5 | 0 | 57.6 | 20.2 | 11.1 | 55.8 | 88.8 | 138.1 | 314.0 | 15.3 |
| 11.8 | 35.7 | 167 | 7.1 | 14.8 | 7.6 | 7.4 | 33.1 | 21.4 | 0 | 61.8 | 9.9 | 5.2 | 30.2 | 48.7 | 125.6 | 219.5 | 19.5 |
| 12.6 | 67.2 | 129 | 39.6 | 13.5 | 8.1 | 2.3 | 27.0 | 24.8 | 14.3 | 68.5 | 15.6 | 8.5 | 43.2 | 68.0 | 112.7 | 248.0 | 24.3 |
| 14.4 | 73.3 | 128 | 49.0 | 13.0 | 11.7 | 9.9 | 34.9 | 6.6 | 0 | 51.4 | 18.2 | 10.0 | 50.4 | 77.1 | 135.0 | 290.7 | 33.6 |
| 16.1 | 49.9 | 76 | 32.5 | 15.4 | 13.0 | 8.2 | 33.2 | 33.2 | 0 | 74.6 | 21.2 | 11.2 | 63.8 | 108.4 | 198.4 | 403.1 | 27.3 |
| 16.4 | 69.5 | 145 | 52.1 | 15.6 | 14.2 | 6.4 | 44.1 | 27.0 | 0 | 77.6 | 27.9 | 14.6 | 86.6 | 139.9 | 342.3 | 611.4 | 35.4 |
| 17.2 | 86.2 | 132 | 47.6 | 18.4 | 13.0 | .5 | 22.3 | 16.8 | 11.2 | 50.8 | 26.7 | 13.5 | 90.8 | 151.6 | 459.0 | 741.8 | 50.9 |
| 19.3 | 70.1 | 208 | 47.9 | 18.2 | 16.6 | 2.4 | 23.2 | 12.0 | 0 | 37.5 | 33.5 | 16.8 | 117.7 | 194.3 | 622.6 | 985.0 | 60.1 |
| 20.4 | 78.4 | 174 | 39.0 | 20.7 | 9.0 | 1.0 | 46.3 | 49.0 | 59.8 | 156.1 | 46.7 | 23.6 | 165.1 | 258.1 | 838.6 | 1332.1 | 49.6 |
| 20.6 | 68.4 | 200 | 40.8 | 16.9 | 14.5 | 11.2 | 45.8 | 15.7 | 0 | 72.8 | 37.0 | 19.0 | 120.6 | 207.6 | 510.9 | 895.2 | 65.3 |
| 25.0 | 95.0 | 200 | 40.8 | 21.0 | 13.3 | 2.3 | 15.7 | 26.8 | 14.1 | 58.9 | 56.6 | 29.5 | 179.9 | 295.7 | 690.3 | 1252.1 | 117.9 |

## Table 34 — Data from tanoak sampled

| | | | | | | Dead crown weight | | | | | Live crown weight | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Branchwood diameter (inches) | | | | | | Branchwood diameter (inches) | | | | | |
| D.b.h. | Tree height | Age | Crown length | Crown width | Diameter of bole at base of crown | 0-0.24 | 0.25-0.99 | 1-2.99 | $3^+$ | Total dead | Foliage | 0-0.24 | 0.25-0.99 | 1-2.99 | $3^+$ | Total live | Bole volume |
| Inches | Feet | Years | Feet | Feet | Inches | Pounds | | | | | | | | | | | Cubic feet |
| 1.3 | 11.7 | 18 | 6.7 | 5.6 | 1.1 | 0.1 | 0.1 | 0 | 0 | 0.2 | 0.7 | 0.5 | 0.8 | 0 | 0 | 2.0 | 0.1 |
| 1.6 | 16.4 | 15 | 5.0 | 3.0 | 0.8 | .1 | .1 | 0 | 0 | .2 | .4 | .3 | .3 | 0 | 0 | 1.0 | .1 |
| 2.0 | 23.4 | 24 | 10.8 | 6.7 | 1.5 | .4 | .7 | 0 | 0 | 1.1 | 1.7 | 1.3 | 1.3 | 0 | 0 | 4.3 | .4 |
| 3.0 | 17.2 | 62 | 9.8 | 8.9 | 2.6 | .7 | 1.4 | 0 | 0 | 2.1 | 2.9 | 2.5 | 5.4 | 4.2 | 0 | 15.0 | .5 |
| 3.2 | 22.8 | 65 | 14.3 | 9.2 | 2.5 | .1 | .4 | 0 | 0 | .5 | 3.4 | 2.8 | 5.6 | 3.9 | 0 | 15.8 | .5 |
| 3.7 | 22.5 | 32 | 14.6 | 6.2 | 3.0 | .4 | .6 | 0 | 0 | 1.0 | 5.8 | 4.8 | 8.8 | 2.8 | 0 | 22.2 | .7 |
| 3.8 | 28.5 | 29 | 18.2 | 6.1 | 3.2 | .3 | .6 | 0 | 0 | .9 | 3.7 | 3.0 | 4.8 | 0.8 | 0 | 12.3 | 1.0 |
| 4.0 | 48.3 | 31 | 11.2 | 2.5 | 1.9 | .1 | 1.5 | .6 | 0 | 2.2 | 1.3 | 1.1 | 2.0 | 1.5 | 0 | 5.8 | 1.7 |
| 4.8 | 47.3 | 46 | 28.3 | 2.6 | 3.5 | .1 | .3 | 0 | 0 | .4 | 3.4 | 2.8 | 5.2 | 3.5 | 0 | 14.9 | 2.8 |
| 5.1 | 43.0 | 47 | 22.5 | 3.0 | 3.8 | .4 | .3 | 0 | 0 | .7 | 3.5 | 2.9 | 4.9 | 4.2 | 0 | 15.4 | 3.0 |
| 5.3 | 40.8 | 42 | 26.1 | 7.9 | 4.1 | .5 | 2.2 | .3 | 0 | 3.0 | 7.0 | 5.8 | 10.9 | .7 | 0 | 24.4 | 2.7 |
| 6.0 | 34.0 | 59 | 21.7 | 11.0 | 4.6 | 0.5 | 1.0 | 0 | 0 | 1.5 | 9.3 | 8.0 | 17.3 | 15.6 | 0 | 50.1 | 4.7 |
| 6.0 | 63.4 | 43 | 42.4 | 6.0 | 4.6 | 0 | .9 | 0 | 0 | .9 | 9.2 | 7.9 | 17.5 | 14.8 | 0 | 49.5 | 2.8 |
| 6.8 | 41.9 | 65 | 27.8 | 12.1 | 5.8 | .6 | 2.4 | 0 | 0 | 3.0 | 12.9 | 11.4 | 29.2 | 34.7 | 0 | 88.2 | 4.1 |
| 8.0 | 36.8 | 55 | 23.1 | 17.6 | 6.9 | 4.2 | 18.2 | 13.2 | 0 | 35.6 | 21.4 | 19.5 | 56.5 | 72.7 | 0 | 170.1 | 5.4 |
| 8.0 | 74.5 | 81 | 31.2 | 8.5 | 4.3 | .4 | 5.7 | .7 | 0 | 6.8 | 12.6 | 10.6 | 20.8 | 8.0 | 0 | 52.0 | 8.1 |
| 8.0 | 56.2 | 59 | 32.1 | 8.8 | 5.7 | 1.2 | 3.8 | 1.9 | 0 | 6.9 | 14.2 | 12.1 | 25.0 | 17.1 | 0 | 68.4 | 7.6 |
| 8.6 | 52.9 | 62 | 33.2 | 19.7 | 6.9 | 1.6 | 7.6 | 2.8 | 0 | 12.0 | 16.6 | 14.6 | 35.8 | 38.1 | 0 | 105.1 | 8.6 |
| 9.4 | 61.0 | 65 | 40.6 | 14.4 | 7.3 | 2.9 | 15.1 | 15.3 | 0 | 33.3 | 28.5 | 25.2 | 64.3 | 77.8 | 0 | 195.8 | 11.0 |
| 9.8 | 53.7 | 57 | 30.1 | 10.0 | 6.6 | .5 | 3.8 | 1.4 | 0 | 5.7 | 18.9 | 16.4 | 37.6 | 37.1 | 0 | 109.9 | 10.0 |
| 10.5 | 54.4 | 63 | 42.9 | 11.8 | 8.9 | 3.0 | 3.3 | 0 | 0 | 6.2 | 34.1 | 29.7 | 70.2 | 69.6 | 0 | 203.5 | 11.6 |
| 11.0 | 66.2 | 120 | 34.9 | 14.9 | 6.9 | .4 | 1.5 | 0.6 | 0 | 2.5 | 24.6 | 22.0 | 58.4 | 74.3 | 0 | 179.5 | 15.3 |
| 11.8 | 59.9 | 83 | 38.6 | 14.9 | 8.6 | 2.1 | 16.3 | 7.6 | 0 | 26.1 | 30.4 | 27.4 | 75.5 | 96.4 | 0 | 229.7 | 12.5 |
| 13.2 | 52.1 | 61 | 42.5 | 20.0 | 12.9 | .5 | 8.4 | 8.7 | 0 | 17.6 | 55.2 | 50.1 | 142.1 | 181.4 | 0 | 428.8 | 19.4 |
| 13.9 | 93.1 | 58 | 74.6 | 15.9 | 11.9 | 1.4 | 3.6 | 2.2 | 0 | 7.3 | 61.0 | 54.4 | 143.7 | 173.1 | 0 | 432.2 | 34.7 |
| 14.9 | 82.6 | 75 | 64.1 | 21.7 | 12.3 | 4.6 | 20.2 | 45.8 | 0 | 70.6 | 58.5 | 52.3 | 140.5 | 169.7 | 0 | 421.0 | 33.0 |
| 17.0 | 70.4 | 97 | 41.2 | 1208 | 12.0 | 1.6 | 9.1 | 12.1 | 0 | 22.8 | 60.1 | 55.3 | 165.6 | 226.4 | 0 | 507.4 | 37.2 |
| 19.6 | 89.8 | 200 | 43.2 | 22.6 | 10.0 | .6 | 6.4 | 19.9 | 6.5 | 33.4 | 60.9 | 56.5 | 177.6 | 227.2 | 0 | 522.2 | 58.0 |
| 20.7 | 72.2 | 137 | 56.4 | 20.8 | 17.0 | 4.0 | 35.4 | 120.6 | 18.5 | 178.4 | 85.2 | 79.9 | 259.8 | 348.3 | 0 | 773.2 | 46.2 |
| 22.3 | 136.4 | 153 | 81.3 | 13.1 | 14.9 | 1.0 | 3.6 | 12.1 | 0 | 16.8 | 57.2 | 52.3 | 153.3 | 200.3 | 0 | 463.1 | 147.5 |
| 25.3 | 112.6 | 200 | 57.8 | 22.6 | 14.8 | 3.1 | 18.6 | 39.4 | 0 | 61.0 | 82.6 | 76.5 | 235.1 | 317.1 | 0 | 711.2 | 164.4 |

## Appendix 3. Equations for Estimating Crown Weight and Bole Volume (Metric Units)

Table 35 — Regression equations for estimating ovendry weight of live crown for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak

$$\ln(w) = A + B\ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -4.5648 | 2.6232 | 53 | 0.94 | 0.3202 |
| Giant chinkapin | -3.7097 | 2.2699 | 30 | .94 | .2154 |
| Bigleaf maple | -2.8534 | 2.1505 | 16 | .93 | .1495 |
| Pacific madrone | -3.8941 | 2.4839 | 31 | .89 | .5410 |
| Tanoak | -3.2304 | 2.2774 | 31 | .94 | .2081 |

Note: w = ovendry weight of live crown (kg), d=diameter at breast height (cm), $s^2$ = mean square error of the residuals.

Table 36 — Regression equations for estimating dead branchwood weight of red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak

$$\ln(dw) = A + B\ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -7.6156 | 2.6243 | 53 | 0.63 | 2.7976 |
| Giant chinkapin | -5.1476 | 2.3038 | 30 | .88 | .4917 |
| Bigleaf maple | -6.4918 | 2.5033 | 16 | .78 | .7131 |
| Pacific madrone | -5.3224 | 2.2936 | 31 | .88 | .4932 |
| Tanoak | -5.1792 | 2.0374 | 31 | .75 | .8375 |

Note: dw = ovendry weight of dead branchwood weight (kg), d=diameter at breast height (cm), $s^2$ = mean square error of the residuals.

**Table 37 — Regression equations for estimating cumulative fractions (f(i)) of live crown component weights for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$f(i)=1/(A + B\,(d)^C)$$

| Fraction | A | B | C | n | $s^2$ | Condition |
|---|---|---|---|---|---|---|
| | | | RED ALDER | | | |
| f(1) | 2.7638 | 0.0620 | 1.3364 | 53 | 0.0006 | None |
| f(2) | 1.2860 | .0288 | 1.3525 | 53 | .0026 | None |
| f(3) | .8847 | .0131 | 1.3021 | 53 | .0057 | If d < 5.3 f(3)=1 |
| f(4) | .9550 | .0002 | 1.9736 | 41 | .0077 | If d < 15.6 f(4)=1 |
| | | | GIANT CHINKAPIN | | | |
| f(1) | 1.6048 | .2979 | .6828 | 30 | .0008 | None |
| f(2) | 1.0700 | .1239 | .7637 | 30 | .0020 | None |
| f(3) | .7312 | .0965 | .6118 | 30 | .0034 | If d < 5.3 f(3)= 1 |
| f(4) | .9669 | .0012 | 1.1786 | 22 | .0010 | If d < 16.7 f(4)= 1 |
| | | | BIGLEAF MAPLE | | | |
| f(1) | 4.6762 | .0163 | 2.0390 | 16 | .0005 | None |
| f(2) | 3.3212 | .0115 | 2.0496 | 16 | .0009 | None |
| f(3) | .9341 | .0021 | 2.1627 | 16 | .0137 | If d < 4.9 f(3)=1 |
| f(4) | .8625 | .0019 | 1.7070 | 15 | .0092 | If d < 12.3 f(4)=1 |
| | | | PACIFIC MADRONE | | | |
| f(1) | 1.6013 | .1060 | 1.3090 | 31 | .0045 | None |
| f(2) | 1.0357 | .0639 | 1.3567 | 31 | .0115 | None |
| f(3) | 1.0281 | .0011 | 2.1850 | 30 | .0118 | None |
| f(4) | .8778 | .0025 | 1.6394 | 27 | .0132 | If d < 10.7 f(4)=1 |
| | | | TANOAK | | | |
| f(1) | 1.7936 | .3031 | .7239 | 31 | .0013 | None |
| f(2) | .9940 | .2303 | .6520 | 31 | .0034 | None |
| f(3) | .8759 | .0446 | .7843 | 31 | .0061 | If d < 3.7 f(3)=1 |
| f(4) | | | | | | f(4)=1.0 for all d |

Note:
f(i) = cumulative fraction for the $i^{th}$ component,
f(1) = fraction of leaf weight,
f(2) = f(1) + (fraction of 0 to 0.62 cm in diameter live branchwood);
f(3) = f(1) + (fraction of 0 to 2.53 cm in diameter live branchwood);
f(4) = f(1) + (fraction of 0 to 7.61 cm in diameter live branchwood);
d = diameter at breast height (cm); and
$s^2$ = mean square error of residuals.

**Table 38 — Regression equations for estimating cumulative fractions (df(i)) of dead crown components for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

| Fraction | n | $r^2$ | $s^2$ | Conditions |
|---|---|---|---|---|
| RED ALDER | | | | |
| $\ln(df(1))=-0.6880-0.0603(d)$ | 52 | 0.43 | 1.3243 | None |
| $\ln(df(2))= 0.02134-0.0342(d)$ | 48 | .47 | .3574 | If $d < 6.2$ $df(2) = 1$ |
| $\ln(df(3))= 0.3473-0.0124(d)$ | 30 | .34 | .0512 | If $d < 28.0$ $df(3)=1$ |
| GIANT CHINKAPIN | | | | |
| $\ln(df(1))=-0.7695-0.0326(d)$ | 30 | .60 | .1737 | None |
| $\ln(df(2))= 0.2022-0.0222(d)$ | 29 | .72 | .0469 | If $d < 9.1$ $df(2)=1$ |
| $\ln(df(3))= 0.1352-0.0063(d)$ | 19 | .28 | .0226 | If $d < 21.5$ $df(3)=1$ |
| BIGLEAF MAPLE | | | | |
| $\ln(df(1))=-1.0444-0.0745(d)$ | 16 | .51 | .7589 | None |
| $\ln(df(2))= 0.0553-0.0260(d)$ | 15 | .53 | .0767 | If $d < 2.1$ $df(2)=1$ |
| $\ln(df(3))= 0.0083-0.0013(d)$ | 12 | .03 | .0064 | If $d < 6.4$ $df(3)=1$ |
| PACIFIC MADRONE | | | | |
| $df(1)=0.3707+0.5714(d)^{0.25}-0.4655(\ln(d))$ | 31 | .56 | .0187 | If $d < 0.9$ $df(1)=1$ |
| $df(2)=1.2671-0.1058(d)^{0.5}$ | 30 | .49 | .0321 | If $d < 6.4$ $df(2)=1$ |
| $df(3)=\exp(0.0281-7.306\times10^{-5}(d)^2)$ | 20 | .34 | .0127 | If $d < 19.7$ $df(3)=1$ |
| TANOAK | | | | |
| $df(1)=0.2985+0.6087(d)^{0.25}-0.4730(\ln(d))$ | 31 | .54 | .0156 | If $d < 0.8$ $df(1)=1$ |
| $df(2)=\exp(-2.810+3.469(d)^{0.25}-1.061(d)^{0.5})$ | 31 | .81 | .0464 | If $d < 10.3$ $df(2)=1$ |
| $df(3)=1.027-0.001354(d)$ | 18 | .16 | .0023 | If $d < 20.0$ $df(3)=1$ |

Note:
$df(i)$ = cumulative fraction for the $i^{th}$ component;
$df(1)$ = fraction of 0 to 0.62 cm in diameter dead branchwood;
$df(2)$ = fraction of 0 to 2.53 cm in diameter dead branchwood;
$df(3)$ = fraction of 0 to 7.61 cm in diameter dead branchwood;
$d$ = diameter at breast height (cm); and
$s^2$ = mean square error of residuals.

**Table 39 — Regression equations for estimating total bole volume inside bark for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$\ln(v) = A + B \ln(d)$$

| Species | A | B | n | $r^2$ | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -8.8272 | 2.4999 | 53 | 0.98 | 0.0708 |
| Giant chinkapin | -9.1304 | 2.5169 | 30 | .99 | .0310 |
| Bigleaf maple | -8.4397 | 2.3050 | 16 | .97 | .5530 |
| Pacific madrone | -8.5385 | 2.2969 | 31 | .97 | .1036 |
| Tanoak | -9.1707 | 2.5010 | 31 | .98 | .0738 |

Note:
$v$ = total bole volume ($m^3$);
$d$ = diameter at breast height (cm); and
$s^2$ = mean square error of residuals.

**Table 40 — Regression equations for estimating the ratio of bole volume below a specified top diameter for red alder, giant chinkapin, bigleaf maple, Pacific madrone, and tanoak**

$$R=1+(A(t^B)(d^C))$$

| Species | A | B | C | n | $s^2$ |
|---|---|---|---|---|---|
| Red alder | -0.3565 | 3.465 | -3.269 | 258 | 0.000828 |
| Giant chinkapin | -.3002 | 3.642 | -3.406 | 133 | .000744 |
| Bigleaf maple | -.3993 | 2.348 | -2.276 | 74 | .002014 |
| Pacific madrone | -.1588 | 2.951 | -2.512 | 127 | .001032 |
| Tanoak | -.1861 | 3.038 | -2.603 | 137 | .001407 |

Note:
$R$ = the fraction of bole volume below a specified top diameter;
$t$ = specified top diameter (cm);
$d$ = diameter at breast height (cm); and
$s^2$ = mean square error of residuals.

Snell, J.A. Kendall; Little, Susan N. Predicting crown weight and bole volume of five western hardwoods. Gen. Tech. Rep. PNW-151. Portland, OR: Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 37 p.

Regression equations are presented for estimating biomass of five western hardwoods: red alder (*Alnus rubra* Bong.), giant chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC.), bigleaf maple (*Acer macrophyllum* Pursh), Pacific madrone (*Arbutus menziesii* Pursh), and tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.). Estimators are given for total crown biomass, cumulative proportions for separating crown weight into foliage and four timelag fuel diameter classes, bark weight, and bole volume (inside bark) to any specified top diameter. With one exception, the equations use diameter at breast height as the only independent variable.

Keywords: Crown weights, volume (log), volume determination methods, hardwoods, biomass.

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# Safety in Bear Country: Protective Measures and Bullet Performance at Short Range

William R. Meehan and John F. Thilenius

## Authors

WILLIAM R. MEEHAN is fisheries research project leader, and JOHN F. THILENIUS is a research wildlife biologist, Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, P.O. Box 909, Juneau, Alaska 99802.

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## Abstract

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Bears are frequently encountered by people working in or enjoying the outdoors. Some government agencies have regulations concerning the firearms their personnel carry for protection against bears.

Guidelines to prevent hazardous encounters with bears are presented, and the performance of commonly used weapons and ammunition is discussed. The ballistic performance of bullets at short range is often considerably different from performance of the same bullet at the longer ranges generally encountered while hunting.

Recommendations are made for weapons and ammunition used as protection from bears.

Keywords: Safety, safety equipment, bears, ballistics, Alaska.

## Introduction

Brown bears (*Ursus arctos)* are found from the seashore to the alpine zone on the islands and mainland along most of the Pacific coast of Alaska.[1] The brown bear is a large, fast-moving animal, unpredictable in its response to humans, and a definite hazard to those who must work in areas inhabited by bears.

The USDA Forest Service in Alaska requires at least one member of each work party to carry a rifle.[2] The most common weapon issued is a bolt-action magazine rifle chambered for the .375 H & H Magnum cartridge. Commercial ammunition is used exclusively. For handiness in the dense brush cover of the Alaska coast, most of these rifles have barrels shortened to 20 inches. Receiver (peep) sights or factory-installed open sights are used; recoil pads and slings are usually present.

In the past, most Forest Service professionals working where brown bears occur had personally acquired experience with firearms. In recent years, however, the Forest Service has employed many persons with little or no experience with firearms, and some with a strong aversion to them. The Forest Service provides training programs in the use of firearms for employees who must work in bear country. The extent and quality of these programs vary from a cursory session on how to load and fire a rifle to a rather intensive course in nomenclature, maintenance and handling of rifles, marksmanship under field conditions, and anatomy and behavior of bears. The rifles used for training are like those to be carried in the field (that is, short-barreled, bolt-action, .375 Magnum). Shooting this rifle may be very unpleasant for some inexperienced persons. They become more apprehensive of the rifle (a known effect) than of the bear (an unknown effect).

The difficulties of training inexperienced persons to properly use large-caliber rifles might be lessened by using smaller caliber weapons. Recoil, muzzle blast, and rifle weight could be decreased, but possibly at the expense of killing power. To provide an inadequate weapon just because it was more pleasant to shoot would be unwise. What, then, constitutes an adequate weapon for protection against bears in the coastal regions of Alaska?

Much has been written about the performance of various cartridges and bullets on big game animals. Most tests have been conducted at ranges of 50 or 75 yards to 300 yards or more, ranges at which hunted game is usually shot.

Little information is available on the performance of cartridges and bullets at ranges that could be considered critical in a life-threatening situation. Distances greater than 15 to 20 yards probably do not constitute a dangerous situation, and some other way to avoid a conflict is probably available.

Our purpose was to evalute the commonly used and readily available cartridges (and weapons) for protection from bears at short range. We selected a distance of 15 yards as the "point of no return"—the distance at which an *obviously aggressive* bear must be stopped or a person risks personal injury or death. We stress "obviously aggressive," a term for a bear that is charging, with the assumed intent of doing bodily harm.

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[1] The same precautions apply to black bears (*Ursus americanus*). The grizzly bear is considered to be the same species as the brown bear.

[2] The policies of other agencies or institutions may differ. Some agencies do not require firearms to be carried; others prohibit them.

# Methods

We selected a range of weapons and ammunition, including those issued by some government agencies to employees working in bear country or carried by the average outdoor person. Other combinations of weapons and ammunition are available, and they may compare favorably with those tested. Interested persons can conduct tests similar to those described here to arrive at their own conclusions for their particular equipment. They will have a better understanding of the capabilities of the weapon and ammunition, and the testing will force the individual to shoot more.

Familiarization with a weapon is at least as important as performance of the bullet in instilling confidence in a person. A person who knows the capability of a firearm is more likely to hold fire until a life-threatening situation is unavoidable or, in a sudden encounter, will react instinctively for defensive purposes.

Most of our testing was done with rifles, but we also evaluated handguns and the 12-gauge shotgun. Handguns are often carried by people working in bear country because they are much more portable and convenient than rifles, especially when work requires both hands. The short-barreled 12-gauge shotgun also has a reputation as a good weapon at close range. We tested both slugs and buckshot loads in the shotgun. In some instances, weapons firing a given cartridge were available with different barrel lengths. We tested these to evaluate the effects of barrel length on bullet performance.

We used ammunition manufactured by several companies, chosen solely on the basis of availability, and made no attempt to compare similar loads of different manufacturers. The ammunition and barrel length of the weapons tested are included in table 1 in the "Results" section.

We fired three shots in random order with each combination of cartridge, bullet weight (or type), and barrel length. This testing method allowed us to measure the penetration of each bullet in a relatively uniform medium, to recover the bullet, and to determine its striking energy. We also measured retained bullet weight and expansion.

To determine penetration and recover fired bullets, we used the testing medium recommended by Hagel (1978), who found that recovered bullets shot into a moistened mixture of 50 percent fine silt and 50 percent fine sawdust (by volume) were similar to bullets removed from various big game animals, including brown bears.

We built an open-end wooden box 12 by 12 by 24 inches to hold the silt-sawdust mixture, covering the open ends with scrap pieces of indoor-outdoor carpet to prevent spillage through bullet holes. To facilitate locating bullets, we placed the mixture in 4- by 10- by 12-inch cardboard file wallets. Six of these tightly filled wallets fit snugly into the box (fig. 1).

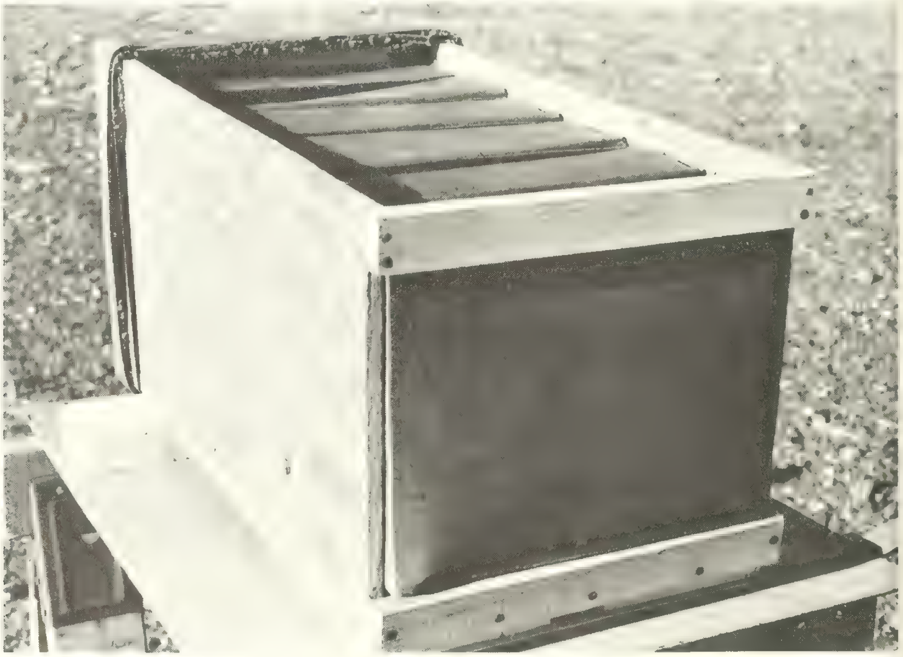

Figure 1. — Bullet recovery box.

After each shot, we located the bullet by sequentially lifting the wallets (fig. 2). We then carefully removed the silt-sawdust mixture from the wallet containing the bullet until the bullet was exposed and measured the distance from the bullet to the front of the box to the nearest 0.5 inch. We removed the bullet, including adjacent fragments, from the medium and placed it in a paper envelope for future examination.

We replaced the silt-sawdust mixture in the wallet where the bullet had stopped and repaired all bullet holes with plastic packaging tape. To avoid bias, we rearranged the front-to-back sequence of all six wallets according to a preselected random sequence after recovering each bullet. We shook the wallets before replacing them and added mixture if needed to keep the content relatively constant. It was necessary to replace all wallets after each six to eight shots. We replaced badly damaged wallets immediately.

We evaluated each cartridge-bullet weight-barrel length combination tested by four ballistic categories: striking energy, penetration, retained bullet weight, and bullet expansion. We also measured bullet velocity because energy is a function of bullet weight and velocity.

We fired all shots through the skyscreens of a Ballistocraft chronograph to determine bullet velocity (fig. 3).[3] We used a 5-ft screen spacing with the first screen at 10 ft. The velocity recorded was considered to be at 12.5 ft. The three-shot average velocity was converted to average velocity at 15 yards from tables provided by Hatcher (1962). Striking energy in foot-pounds (ft-lb) was determined from the formula $E = WV^2/450,240$, where W is the bullet weight in grains (gr), V is the velocity in feet per second, and $450,240 = 2 \times 32.16 \text{ ft/s}^2 \times 7000 \text{ gr/lb}$ (Hatcher 1962).

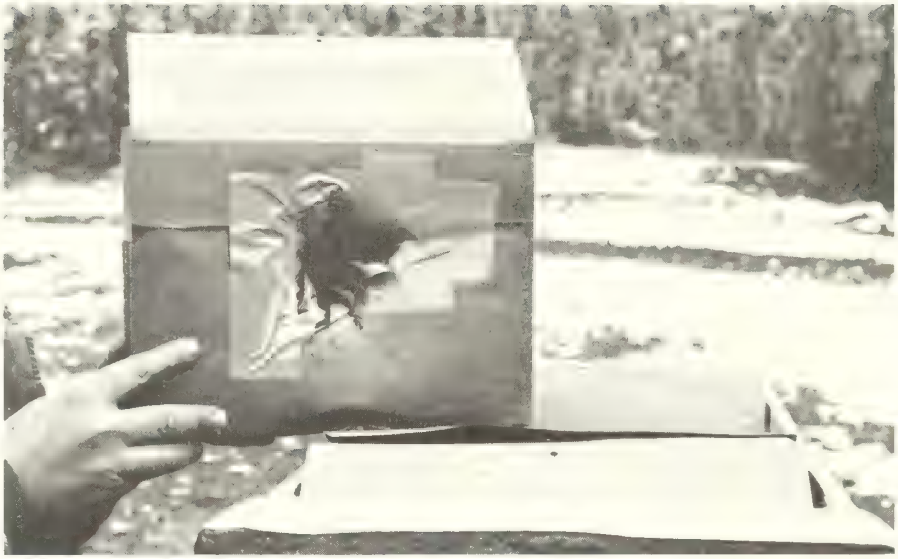

Figure 2 — Bullet box wallet insert.

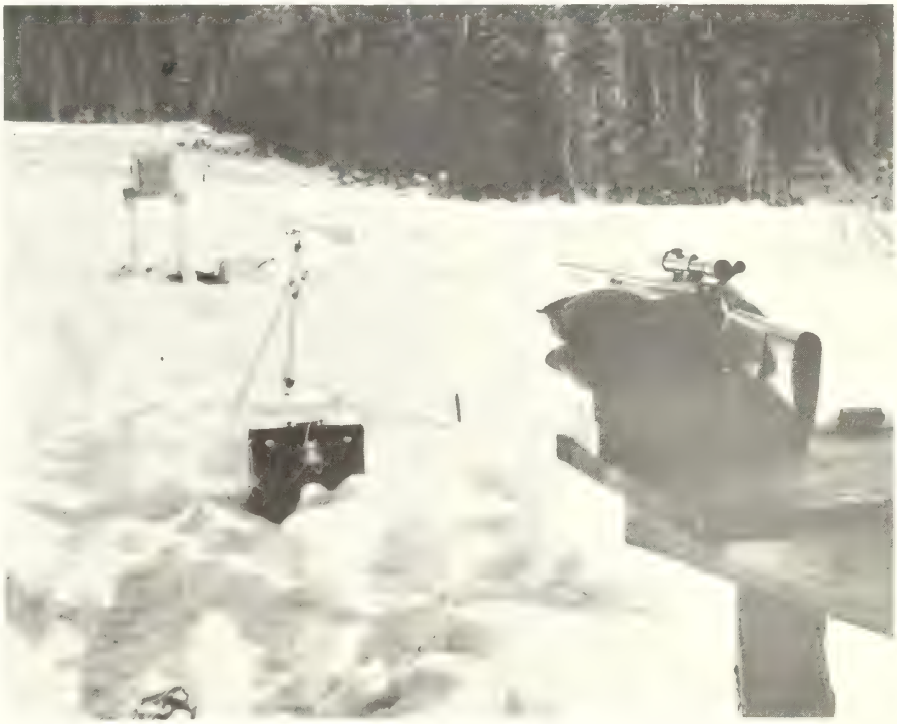

Figure 3. — Cartridge performance testing facility, showing chronograph and bullet recovery box.

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[3] Names of products are for information only; the chronograph was the personal property of one of the authors

## Results and Discussion

We washed recovered bullets and bullet fragments in hot water and detergent to remove silt-sawdust medium. We rinsed, dried, and weighed each to the nearest grain. To determine expansion, we measured to the nearest 0.01 inch the maximum diameter of the bullet (or the largest fragment) and the diameter at 90° to the maximum diameter. The cross-sectional area of this ellipse was determined by the formula $A = 3.1416\,ab$, where $a$ = maximum diameter and $b$ = diameter at 90° to $a$. Both retained bullet weight and expansion were expressed as a percentage of the weight and cross-sectional area of an unfired bullet pulled from a cartridge identical to that fired in the tests.

We determined the free recoil energy using the method described by Mannes (1981). Although recoil is not directly involved in short-range terminal ballistics, it is a significant factor in the overall evaluation of rifles used for protection from bears.

Because we had no unbiased way to determine the relative importance of each ballistic category, we considered each to be equally important. Our first step in evaluating overall ballistic performance was to calculate the average value in each category for the three shots fired from each test combination. We then divided each average by the maximum average value in its category to convert it to a relative proportion of the maximum value encountered during the tests. We rounded the quotient to two significant decimal places and multiplied by 100 to eliminate decimals. This transformation also eliminated the different category units and allowed all four to be arithmetically combined into a single performance score. We calculated this score by multiplying the four relative scores of each test combination. To eliminate the use of unwieldy eight-digit numbers as scores, we divided the product by 100,000 and rounded the quotient to the nearest whole number. This provided a two- or three-digit score for each test combination, which we ranked in highest to lowest order.

Results of the tests are presented in table 1 and figure 4. We discuss each cartridge tested in the following categories: (1) large-, medium-, and small-caliber magnum rifle cartridges; (2) large-, medium-, and small-caliber standard rifle cartridges; (3) large- and medium-caliber magnum and standard handgun cartridges, and (4) the 12-gauge shotgun.

### Large-Caliber Magnum Rifle Cartridges

**.458 Winchester Magnum.** — In overall ballistic performance, the .458 ranked first. Bullet penetration was the deepest of all the cartridges tested — average depth, 19 inches. Striking energy was 79 percent of the .460 Weatherby (ranked second), part of which may be attributed to the extra 10 gr of bullet weight in the .458. The bullet expanded well (4.6 times) and retained 82 percent of the unfired weight. The 510-gr Winchester factory bullets used in the .458 did not fragment, but the 500-gr bullets of the .460 Weatherby did. This was the major reason for the first-place ranking.

Recoil in the 9.4-lb rifle was 54.7 ft-lb or about 71 percent of that of the .460 in a rifle that was 1.3 lb heavier. The lesser recoil in a lighter rifle and better bullet performance make the .458 Winchester preferable to the .460 Weatherby. A short-barreled, bolt-action .458 would be an excellent rifle for an experienced rifleman. Shortening the barrel to 22 or even 20 inches should not reduce ballistic performance much. Any weight reduction, however, would increase recoil.

**.460 Weatherby Magnum.** — The .460 Weatherby Magnum cartridge ranked second in overall performance. The large-caliber, heavy bullet at relatively high velocity had good, but not the deepest, penetration. Although the chronographed velocity did not approach the advertised velocity, bullet energy exceeded that of the .458 Winchester by over 1300 ft-lb. Average retained bullet weight was 65 percent of the unfired weight. The bullets had a tendency to fragment. It appears the high striking energy exceeded the design limits of the bullet at the short test range. Cross-sectional area expansion was adequate and overall bullet performance good, but not the best.

The high overall performance of the .460 Weatherby was obtained in a heavy-recoiling, 10.7-lb rifle with a 26-inch barrel. We used a Weatherby Mark V rifle equipped with a receiver sight. It was very difficult to use this sight because of the high comb[4] of the Weatherby stock. This plus the heavy recoil made it very uncomfortable to shoot. The stock shape, heavy weight, and long barrel detract from the utility of the rifle in the heavy bush of coastal Alaska. This could be ameliorated if the rifle were remodeled, but shortening the barrel to 20 inches would lower velocity and energy. This might be beneficial if it also reduced the tendency of the bullet to fragment; however, there is little reason to reduce the .460 if a .458 is available.

A short-barreled .460 would have tremendous muzzle blast, and the recoil of a .460 Weatherby less than 10 lb in weight would be so severe that it would be difficult for the shooter to recover from the recoil and operate the bolt to rapidly chamber a second cartridge. For these reasons, we think the .460 Weatherby rifle is generally a poor choice for protection from bears in coastal Alaska.

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[4] The comb is the top portion of the stock where the shooter's cheek rests.

**Table 1 — Short-range ballistic performance**

| | Ranking | | Bullet | | | Ballistic performance | | | | | Firearm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cartridge | Score | Rank | Weight | Type[1] | Brand[2] | Velocity, 15 yd | Energy, 15 yd | Penetration | Retained weight | Expansion ratio | Recoil | Weight | Barrel length |
| | | | *Grains* | | | *Ft/s* | *Ft-lb* | *Inches* | *Percent* | *Times* | *Ft-lb* | *Lb* | *Inches* |
| Rifle:[3] | | | | | | | | | | | | | |
| .458 Win. Mag. | 538 | 1 | 510 | RSP | W-W | 2074 | 4871 | 19.0 | 82 | 4.6 | 54.7 | 9.4 | 24 |
| .460 Wby. Mag. | 487 | 2 | 500 | RSP | WBY | 2364 | 6204 | 17.2 | 65 | 3.8 | 76.8 | 10.7 | 26 |
| .375 H & H Mag. (L)[4] | 301 | 3 | 300 | SSP | W-W | 2541 | 4903 | 16.8 | 67 | 4.0 | 41.1 | 8.6 | 24 |
| .338 Win. Mag. (S) | 260 | 4 | 300 | RSP | W-W | 2314 | 3568 | 16.2 | 61 | 4.8 | 35.6 | 7.4 | 20 |
| .375 H & H Mag. (L) | 239 | 5 | 270 | RSP | R-P | 2659 | 4241 | 14.2 | 64 | 4.0 | 37.2 | 8.6 | 24 |
| .338 Win. Mag. (S) | 213 | 6 | 200 | PSP | W-W | 2699 | 3235 | 15.0 | 69 | 4.2 | 28.9 | 7.4 | 20 |
| .338 Win. Mag. (S) | 197 | 7 | 250 | SSP | W-W | 2507 | 3491 | 12.2 | 57 | 5.3 | 33.4 | 7.4 | 20 |
| .338 Win. Mag. (L) | 191 | 8 | 200 | PSP | W-W | 2834 | 3563 | 12.3 | 60 | 4.7 | 26.0 | 8.6 | 24 |
| .338 Win. Mag. (L) | 186 | 9 | 300 | RSP | W-W | 2360 | 3710 | 16.8 | 57 | 3.4 | 31.2 | 8.6 | 24 |
| .375 H & H Mag. (S) | 185 | 10 | 300 | SSP | W-W | 2401 | 3843 | 13.8 | 63 | 3.6 | 44.1 | 7.2 | 20.5 |
| .30-06 U.S. | 157 | 11 | 220 | RSP | R-P | 2261 | 2498 | 17.7 | 65 | 3.6 | 15.3 | 8.8 | 22 |
| .30-06 U.S. | 153 | 12 | 180 | RSP | R-P | 2456 | 2411 | 13.2 | 71 | 4.4 | 14.8 | 8.8 | 22 |
| .444 Marlin | 146 | 13 | 240 | FSP | R-P | 2237 | 2668 | 11.0 | 72 | 4.5 | 27.6 | 7.3 | 22 |
| .358 Winchester | 142 | 14 | 200 | SSP | W-W | 2366 | 2488 | 12.0 | 71 | 4.4 | 33.4 | 7.4 | 22 |
| 7 mm Rem. Mag. | 141 | 15 | 175 | PSP | W-W | 2709 | 2853 | 13.0 | 44 | 5.6 | 18.5 | 9.1 | 24 |
| .375 H & H Mag. (S) | 137 | 16 | 270 | RSP | R-P | 2456 | 3735 | 12.3 | 50 | 3.9 | 39.4 | 7.2 | 20.5 |
| .45-70 U.S. (S) | 133 | 17 | 300 | HSP | FED | 1573 | 1649 | 13.0 | 84 | 4.8 | 15.6 | 7.1 | 20 |
| .308 Winchester | 128 | 18 | 180 | RSP | FED | 2430 | 2360 | 12.7 | 73 | 3.9 | 13.6 | 8.4 | 22 |
| .45-70 U.S. (L) | 124 | 19 | 300 | HSP | FED | 1666 | 1849 | 11.0 | 96 | 4.1 | 18.6 | 7.8 | 22 |
| .358 Norma Mag. | 115 | 20 | 250 | PSP | NOR | 2730 | 4139 | 15.2 | 41 | 2.9 | 25.0 | 8.4 | 24 |
| 8 mm Rem. Mag. | 107 | 21 | 185 | PSP | R-P | 2991 | 3676 | 10.7 | 32 | 5.5 | 29.1 | 9.4 | 24 |
| .300 Wby. Mag. | 104 | 22 | 180 | PSP | WBY | 3033 | 3678 | 15.2 | 46 | 2.6 | 28.0 | 9.6 | 24 |
| .338 Win. Mag. (L) | 100 | 23 | 250 | SSP | W-W | 2594 | 3735 | 14.7 | 45 | 2.6 | 30.0 | 8.6 | 24 |
| .350 Rem. Mag. | 93 | 24 | 200 | SSP | R-P | 2568 | 2931 | 12.2 | 52 | 3.2 | 34.5 | 6.4 | 18.5 |
| 7x57 mm Mauser | 87 | 25 | 175 | RSP | FED | 2419 | 2274 | 13.8 | 52 | 3.6 | 12.7 | 8.9 | 24 |
| 12-ga x 2¾ inch | 74 | 26 | 438 | LRN | FED | 1398 | 1902 | 15.3 | 96 | 1.7 | 26.1 | 7.1 | 20 |
| .45-70 U.S. (L) | 65 | 27 | 405 | RSP | R-P | 1322 | 1572 | 15.8 | 93 | 2.1 | 17.7 | 7.8 | 22 |
| .300 Win. Mag. | 60 | 28 | 200 | PSP | FED | 2699 | 3237 | 15.2 | 36 | 2.2 | 25.9 | 7.8 | 24 |
| .300 Wby. Mag. | 59 | 29 | 220 | RSP | WBY | 2798 | 3826 | 15.2 | 34 | 2.0 | 30.8 | 9.6 | 24 |
| .45-70 U.S. (S) | 50 | 30 | 405 | RSP | R-P | 1211 | 1319 | 17.8 | 98 | 1.4 | 13.6 | 7.1 | 20 |
| 8 mm Rem. Mag. | 49 | 31 | 220 | PSP | R-P | 2779 | 3773 | 12.8 | 28 | 2.5 | 18.9 | 9.4 | 24 |
| .44 Rem. Mag. (L) | [5] 47 | 32 | 240 | LGC | R-P | 1401 | 1046 | 11.5 | 97 | 2.6 | 13.9 | 3.1 | 7.5 |
| .300 Win. Mag | 44 | 33 | 180 | PSP | FED | 2959 | 3268 | 10.3 | 30 | 2.8 | 26.3 | 7.8 | 24 |
| Handgun: | | | | | | | | | | | | | |
| .44 Rem. Mag. (L) | [6] 77 | 1 | 240 | LGC | R-P | 1401 | 1046 | 11.5 | 97 | 2.6 | 13.9 | 3.1 | 7.5 |
| .44 Rem. Mag. (M) | 64 | 2 | 240 | LGC | R-P | 1317 | 925 | 12.2 | 97 | 2.3 | 14.1 | 3.2 | 6.5 |
| .44 Rem. Mag. (L) | 63 | 3 | 240 | JSP | W-W | 1383 | 1019 | 14.5 | 94 | 1.8 | 12.4 | 3.1 | 7.5 |
| .44 Rem. Mag. (S) | 60 | 4 | 240 | LGC | R-P | 1265 | 853 | 11.3 | 97 | 2.5 | 15.8 | 2.9 | 5 |
| .44 Rem. Mag. (S) | 59 | 5 | 240 | JSP | W-W | 1370 | 1001 | 9.5 | 97 | 2.5 | 15.1 | 2.9 | 5 |
| .44 Rem. Mag. (M) | 57 | 6 | 240 | JSP | W-W | 1348 | 969 | 11.5 | 96 | 2.2 | 16.4 | 3.2 | 6.5 |
| .357 S&W Mag. | 27 | 7 | 158 | JSP | CCI | 1226 | 528 | 9.5 | 99 | 2.1 | 7.2 | 2.3 | 4 |
| .45 Colt (L) | 13 | 8 | 255 | LRN | W-W | 825 | 386 | 14.3 | 98 | 1.0 | 5.9 | 2.6 | 7.5 |
| .45 Auto | 12 | 9 | 230 | SMJ | R-P | 819 | 343 | 14.2 | 100 | 1.0 | 5.2 | 2.4 | 5 |
| .41 Rem. Mag. | 11 | 10 | 210 | LFN | R-P | 952 | 423 | 10.5 | 97 | 1.0 | 6.0 | 2.4 | 4.8 |
| .45 Colt | 11 | 11 | 225 | LHP | FED | 813 | 330 | 13.3 | 97 | 1.0 | 4.6 | 2.6 | 7.5 |
| .45 Colt (S) | 10 | 12 | 255 | LRN | W-W | 796 | 359 | 11.8 | 97 | 1.0 | 5.9 | 2.4 | 4.8 |
| .44 S&W Spec. | 9 | 13 | 246 | LRN | W-W | 745 | 303 | 12.1 | 99 | 1.0 | 3.9 | 3.1 | 7.5 |

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[1] RSP = round nose soft point; SSP = semipointed soft point; PSP = pointed soft point; FSP = flat nose soft point; HSP = hollow soft point; LRN = lead round nose; LGC = lead gas-check; JSP = jacketed soft point, SMJ = solid metal jacket; LFN = lead flat nose; LHP = lead hollowpoint.

[2] W-W = Winchester-Western; R-P = Remington-Peters; FED = Federal; WBY = Weatherby; NOR =Norma; CCI = Speer.

[3] All rifles except 1 shotgun and 1 handgun included for comparison.

[4] L = long barrel; M = medium barrel; S = short barrel; applies only when the same cartridge was tested in different length barrels.

[5] Score calculated on same basis as rifles and shotgun.

[6] Score calculated for handguns only; not equal to rifle scores.

## Medium-Caliber Magnum Rifle Cartridges

**.375 H & H Magnum.** — The .375 H & H Magnum was one of the cartridges tested with different bullet weights and in rifles with different barrel lengths. With the 300-gr bullet in a rifle with a 24-inch barrel, it ranked 3; with the 270-gr bullet in the same length barrel it ranked 5. Performance rankings for the rifle with a 20.5-inch barrel were 10 for the 300-gr bullet and 16 for the 270-gr bullet. Energy exceeded 4200 ft-lb in the longer barreled rifle for both bullets and 3700 ft-lb for the shorter barreled rifle. Bullets of both weights fired in the longer barreled rifle penetrated about 2 inches deeper, but there were only minor differences in retained bullet weight and relative bullet expansion. Velocity losses in the shorter barrel were 203 ft/s for 270-gr bullets and 140 ft/s for 300-gr bullets. Chronographed velocities were close to those advertised for the rifle with a 24-inch barrel.

Recoil in the 8.6-lb rifle with a 24-inch barrel ranged from 37 to 41 ft-lb. The 7.2-lb rifle with the shorter barrel had heavier recoil — 39 and 44 ft-lb for the 270- and 300-gr bullets, respectively. The heaviest recoil value was 57 percent of the recoil value of the .460 Weatherby and 81 percent of the .458 Winchester.

The similarity in overall ballistic performance and not too severe recoil make the lighter rifle with the shorter barrel preferable, although some ballistic performance is lost. The 300-gr bullet is preferable to the 270-gr bullet. This type of .375 rifle is commonly carried in coastal Alaska. The rifle must be rated at a capacity of three cartridges (magazine capacity) since it is unsafe to have a cartridge loaded in the chamber and depend on a mechanical safety to prevent discharge. Moving through thick brush, leaning the rifle against a tree, or laying it on the ground while working can cause inadvertent release of the safety on most bolt-action rifles. This applies to bolt-action rifles with the possible exception of those made on military actions, such as the Mauser or Springfield with their 180° safety levers, which are slow to operate; however, few .375 caliber rifles have such safeties. Regardless, the .375 H & H Magnum is an excellent cartridge for protection from bears at close range. Our tests merely reinforced its already excellent reputation.

**.338 Winchester Magnum.** — The .338 Winchester was tested with three bullet weights (200-, 250-, and 300-gr) and in rifles with two barrel lengths, 24 and 20 inches. The recently available 225-gr bullet was not produced at the time we made the tests, and the 250-and 300-gr bullets are no longer manufactured. The shorter barreled rifle gave slightly better overall ballistic performance. With the 300-gr bullet it was ranked 4 and was close to the 300-gr .375 H & H with a 4 inch longer barrel, although the .375 H & H had 1335 ft-lb more striking energy with a 300-gr bullet. The 300-gr .338 Winchester bullet had only 0.6 inch less penetration, retained slightly more bullet weight, and had slightly greater expansion than the 300-gr bullet in the .375. The 250-gr bullet gave much poorer overall ballistic performance than either the 300- or the 200-gr bullet. The .338 with the 200-gr bullet ranked 6 and 8, the rifle with the shorter barrel giving the better performance; it averaged 15 inches of penetration compared with 12.2 inches for the 250-gr bullet.

The 250-gr bullet had a tendency to shatter in the test medium which may account for the lower penetration. The 200-gr bullet should be selected if the 300-gr is not available. In the 7.4-lb .338 rifle with a 20-inch barrel, recoil was 35.6 ft-lb with the heaviest bullet. This was somewhat less than in the .375 with the same weight of bullet in both light and heavy rifles. The 200-gr bullet load generated 28.9 and 26.0 ft-lb of recoil in the rifles with 20- and 24-inch barrels, respectively, and was not uncomfortable to shoot. Shortening the barrel seemed to lower velocities only slightly for the 300- and 250-gr bullets, but a greater reduction in velocity occurred for the 200-gr bullet (see table 1). Chronographed velocities were similar to advertised velocities.

The reasonable recoil in a light, short-barreled rifle with impressive overall ballistic performance makes the .338 Winchester cartridge a good choice for rifles for protection from bears. Limitations are the same as for the other bolt-action magnums — low magazine capacity and the safety hazard inherent in a mechanical safety. Discontinuation of the 300-gr bullet in factory loading decreases the potential of the .338 as a cartridge for close-range protection.

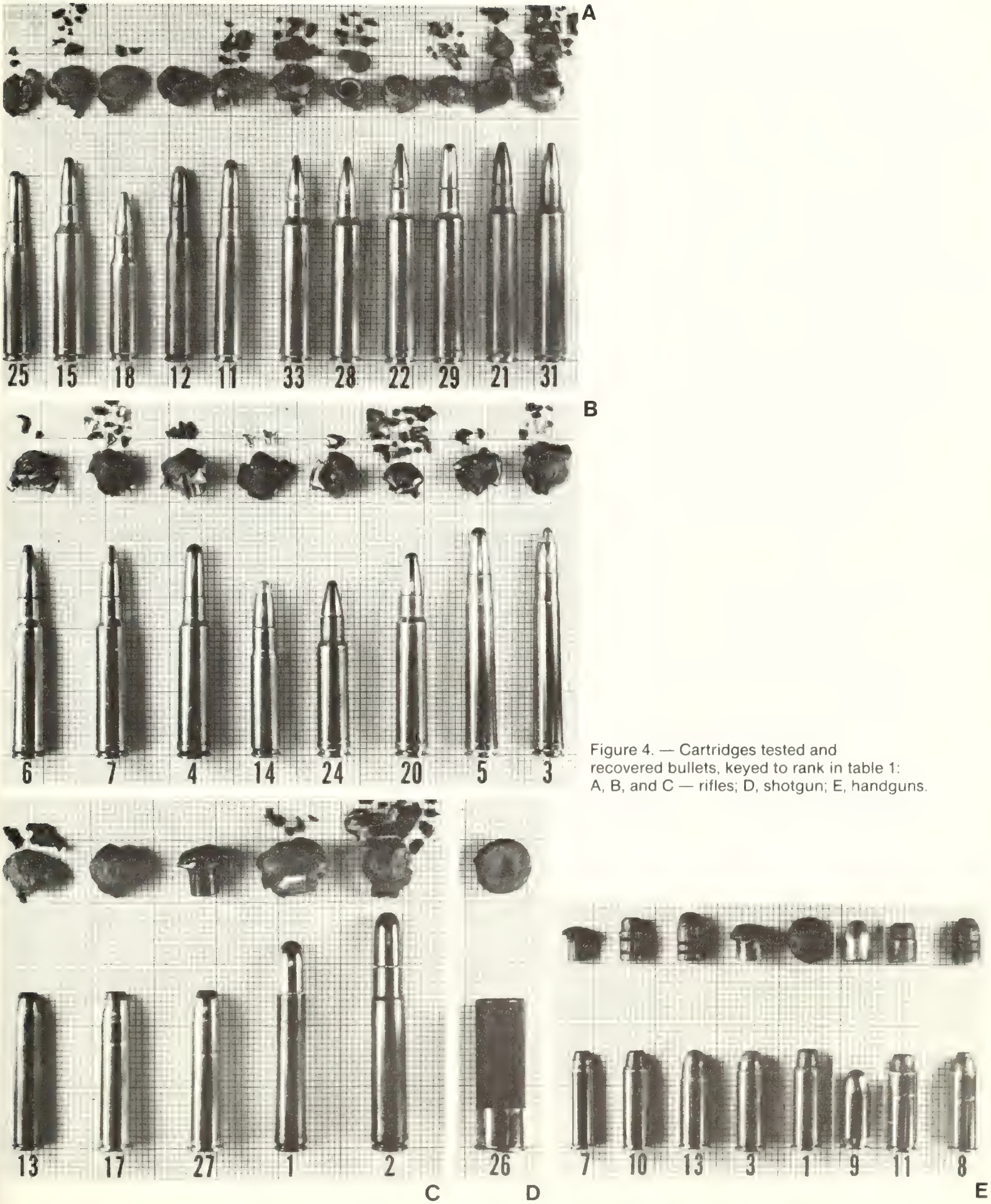

Figure 4. — Cartridges tested and recovered bullets, keyed to rank in table 1: A, B, and C — rifles; D, shotgun; E, handguns.

**.358 Norma Magnum.** — The .358 Norma Magnum was ranked 20 in our tests. Its relatively low ranking was mainly due to poor retained bullet weight and relative expansion. The 250-gr Norma factory bullets did not hold together well in the test medium. Retained bullet weight was low since this parameter is based on the largest recovered bullet fragment. The .358 Norma bullet reacted similarly to the 250-gr bullet in the longer barreled .338 Winchester (ranked 23). Although the bullets fragmented, penetration of the largest fragments was relatively deep.

Recoil of the .358 Norma Magnum was similar to recoil in the .338 and .375 rifles with 250- and 270-gr bullets, respectively. If suitable bullets were available in factory-loaded ammunition, the .358 Norma would be an excellent cartridge for rifles for protection from bears. Other disadvantages are the cost and difficulty of obtaining the ammunition. Because of these considerations, the .358 Norma Magnum is not recommended.

### Small-Caliber Magnum Rifle Cartridges

**7 mm Remington Magnum.**—The 7 mm Remington Magnum was the highest ranked (15) of the small-caliber magnum cartridges. Bullet penetration was only moderately deep, and the bullets fragmented to some extent as the average retained weight was only 44 percent. Bullet expansion was the highest of all the bullets tested; this attribute gave the 7 mm Remington its relatively high overall rank. In contrast, most other small-caliber magnum cartridges had relatively poor expansion values. The exception was the 8 mm Remington 185-gr bullet which had high expansion but also had substantial weight loss and poor penetration. The striking velocity of the 7 mm Remington 175-gr bullet was barely 2700 ft/s at 15 yd, well below what would be expected from published ballistic data; nevertheless, it appears the design limits of the bullet were exceeded.

Recoil was calculated at 18.5 ft-lb in the 9.1-lb rifle used. This is mild, but greater than that of the 220-gr .30/06 cartridge from a lighter weight rifle. There does not appear to be any special reason for selecting the 7 mm Remington for short-range protection. Its overall ballistic performance is marginal for this purpose.

**.300 Weatherby, .300 Winchester, 8 mm Remington Magnums.** — These three cartridges are considered together. All are loaded with moderate-weight bullets (180- to 185-gr) at velocities between 2950 and 3050 ft/s and heavier bullets (200- to 220-gr) between 2700 and 2800 ft/s. These high velocities with moderately heavy bullets resulted in striking energies that exceed the design level of the bullets, especially the heavier ones. Fragmentation was prevalent for these bullets, and weight losses were 60 percent or more. The average weight of the largest fragment of the 8 mm Remington 220-gr bullet was only 28 percent of the unfired bullet weight. The 185-gr bullet in the 8 mm Remington was the best of the lighter weight bullets in these three cartridges, with a ranking of 21 in overall performance. Penetration was poor, however, and fragmentation excessive. The 180-gr bullet in the .300 Winchester also had poor penetration and substantial weight loss, as well as relatively poor expansion, all of which contributed to its last place ranking. The ranking of the .300 Weatherby with the 180-gr bullet was a disappointment. Factory cartridges are loaded with 180-gr Nosler partition bullets which have an excellent reputation. In our test, the 180-gr bullets in the .300 Weatherby penetrated well but lost over 50 percent of the unfired bullet weight and did not have particularly good expansion. The 180-gr bullet was much better in overall performance than the 220-gr bullet which fragmented badly. This was also true for the 200-gr bullet in the .300 Winchester.

None of the small-caliber magnum cartridges can be considered good selections for protection from bears at short range because of the excessive fragmentation of bullets.

### Large-Caliber Standard Rifle Cartridges

**.45-70 U.S.** — We tested the .45-70 in two bullet weights (300- and 405-gr) and in rifles with two barrel lengths (20 and 22 inches). Both rifles were Marlin 1895 lever-action. In both, the 300-gr bullet ranked much higher than the 405-gr bullet, primarily because of the poor expansion of the 405-gr bullets. At the 1200-1300 ft/s striking velocity, some of these bullets acted as solids and penetrated as much as 24 inches. This was the greatest penetration recorded in the tests. The 300-gr bullets, with 300 to 400 ft/s more velocity, did not penetrate deeply but held together and expanded well and uniformly. Low velocities resulted in low striking energy. Shortening the barrel by 2 inches had no effect on the performance of the bullet; in fact, the rifle with the 20-inch barrel performed better with the 300-gr bullet than did the longer barreled rifle. Recoil in this rifle, which weighed less than 8 lb, was much less severe than in the large-caliber magnums; it is thus not a detracting factor. The poor action of the 405-gr bullets may limit their use for protection from bears. The 300-gr bullets in the commercial ammunition we used are designed for animals the size of deer and may expand too rapidly and lack sufficient penetration for use against bears. In our test they did not fragment too badly. The lack of a proper bullet is unfortunate. The .45-70 can be obtained in a compact, moderate weight, lever-action rifle that may be easier and faster to operate, particularly for left-handed people.

Perhaps the current reinterest in .45-70 rifles will cause the manufacturers to produce a more suitable bullet. We do not consider factory-loaded .45-70 ammunition particularly suitable for a rifle for protection from bears, especially with the 405-gr bullet.

**.444 Marlin.** — In overall performance, the .444 Marlin cartridge ranked 13. Although penetration was not especially deep, the bullet held together and expanded well. Striking velocity exceeded 2200 ft/s in the rifle with the 22-inch barrel. Consequently, striking energy was over 2650 ft-lb.

The flat nose soft point bullet loaded in the .444 Marlin appears similar to that of the .44 Remington Magnum revolver cartridge. Although the .444 cartridge ranked relatively high, we have reservations about shooting at a brown bear with a bullet designed for a handgun cartridge. If a well-constructed bullet of about 300-gr weight was available in factory-loaded ammunition, the .444 could become an adequate cartridge for protection from bears. We were unable to obtain the recently introduced cartridges factory-loaded with a 265-gr bullet.

## Medium-Caliber Standard Rifle Cartridges

**.358 Winchester, .350 Remington Magnum.**[5] —The .358 Winchester and the .350 Remington Magnum were included to fill out the full range of cartridge possibilities. The .358 Winchester ranked higher (14) than the .350 Remington (24). Better retained bullet weight and greater bullet expansion accounted for the higher rank of the .358 Winchester. These two cartridges illustrate the poor relation between penetration and striking energy. The .350 Remington had 443 ft-lb greater striking energy than the .358 Winchester, but only 0.2 inch more penetration. In our tests there was relatively little difference between the .358 Winchester and some much larger, more powerful cartridges. We were unable to obtain 250-gr bullets for either cartridge. The 200-gr bullet in the .358 Winchester, however, seems to be a well-balanced load. The relatively low striking energy reduced the ranking of the .358 Winchester, and, to some extent, the .350 Remington. In addition, the average retained bullet weight for the .350 Remington was 52 percent compared with 71 percent for the .358 Winchester.

Recoil was moderate and similar in both rifles. The .350 Remington rifle weighed a pound less than the .358 Winchester rifle. Both cartridges can be considered minimal for protection from bears at close range.

## Small-Caliber Standard Rifle Cartridges

**.30-06 U.S.** — With the 220-gr bullet the .30-06 ranked 11, and with the 180-gr bullet it ranked 12 in overall ballistic performance. The 220-gr bullet penetrated 17.7 inches. This was 4.5 inches deeper than the 180-gr bullet, but the striking energy of the two bullets was similar. The 220-gr bullet had only 87 ft-lb greater energy at 15 yd. The 180-gr bullet retained slightly more weight than the 220-gr bullet and also expanded slightly more relative to the initial cross-sectional area. The 180-gr bullet also had less tendency to fragment than did the 220-gr bullet.

Recoil for both bullet weights was mild compared with large- and medium-bore magnums. Chronographed velocities were much lower than advertised. The 220-gr bullet averaged 2261 ft/s for three shots, whereas the 180-gr bullet averaged only 2456 ft/s velocity at 15 yd.

The light recoil potential and the good overall ballistic performance make the .30-06 a reasonable cartridge for protection from bears. Because of the deeper penetration of the 220-gr bullet, it is better than the 180-gr bullet. For inexperienced persons or those of small stature, the .30-06 with 220-gr bullets may be a better choice than one of the large- or medium-bore magnums. A 7- to 7.5-lb .30-06 with a 20-inch barrel would be a handy, portable rifle for protection from bears. The use of the .30-06 has a major advantage over use of magnum cartridges —magazine capacity is increased to five rounds. Another advantage is the availability of left-handed bolt-action rifles in this caliber. The .30-06 is also available in slide-action and semiautomatic rifles.

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[5] The .350 Remington Magnum was considered a standard cartridge because its case has a relatively small powder capacity.

**.308 Winchester, 7x57 mm Mauser.** — These two cartridges were included in the tests to represent the "minimal" cartridges that might be used for protection from bears. They are also often used by deer hunters. The ranges of the brown bear and the Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) overlap through much of coastal Alaska, and deer hunters need protection from bears similar to that of working professionals. Of the two cartridges, the .308 Winchester ranked higher (18) than the 7x57 mm Mauser (25). The greatest difference was in retained bullet weight. The 7x57 mm Mauser bullets lost almost half their weight, whereas the .308 Winchester bullets shed less than 25 percent of their original weight. The 7x57 mm bullets had about 1 inch deeper penetration, but the range in penetration varied less in the .308 Winchester. Penetration of the 175-gr bullet in the 7x57 mm Mauser was greater than that of the same weight bullet in the 7 mm Remington Magnum, although striking energy was almost 600 ft-lb less in the 7x57 mm Mauser.

Recoil was mild for both cartridges; however, both of the rifles used weighed more than 8 lb. We do not recommend either of these calibers for protection from bears.

## Large-Caliber Magnum Handgun Cartridge

**.44 Remington Magnum.** — The .44 Remington Magnum load fired from a handgun ranked 32 compared with loads fired from rifles and the 12-gauge shotgun but ranked first compared with other handgun cartridges (table 1). It was included with the rifle cartridges for comparison purposes only and was ranked by the rifle and shotgun attributes. In overall performance it was similar to the 8 mm Remington Magnum 220-gr bullet and the .300 Winchester Magnum 180-gr bullet. The 240-gr lead gas-check bullet held together well, penetrated more than 11 inches, and expanded moderately well. Only the low energy value reduced its ranking in the rifle and shotgun category.

The .44 Remington Magnum was by far the best handgun cartridge. Two bullets (240-gr lead gas-check; 240-gr jacketed soft-point) were tested in revolvers with 5-, 6.5-, and 7.5-inch barrels. No substantial difference was observed between the velocities of the two bullets in the same length of barrel, but the lead gas-check bullet ranked higher overall in ballistic performance than did the jacketed soft-point bullet. The lead gas-check bullet ranked 1, 2, and 4. Generally, the lead gas-check bullet expanded well and retained almost all its original weight. The jacketed soft-point bullet had somewhat greater average penetration, but also much greater variation in penetration than the lead gas-check bullet. It also had slightly greater striking energy.

As expected, recoil was greater in the .44 Magnum revolvers than in any other handgun tested. It ranged from 16.4 ft-lb in the 6.5-inch barrel revolver with the jacketed soft-point load to 12.4 ft-lb in the 7.5-inch barrel revolver with the same load.

The superiority of the .44 Remington Magnum makes it the cartridge choice for a *backup* weapon. A revolver using this cartridge should not be considered a primary weapon for protection from bears.

The slight difference in overall ballistic performance between long and short barrels makes a revolver with a short barrel just as effective as one with a longer barrel. A short-barreled revolver is lighter, easier to carry, and may be drawn from a holster more quickly. Carried in a cross draw or shoulder holster, a short-barreled .44 Magnum revolver is at hand at all times. When work requires both hands, a rifle is often put aside. A rifle a few feet away is useless for protection from bears, but a handgun can be useful. Although much practice is necessary to become proficient with a shoulder arm, even more practice is required to attain competence with a handgun.

## Other Large- and Medium-Caliber Handgun Cartridges

**.357 S&W Magnum, .41 Remington Magnum, .44 S&W Special, .45 Auto, .45 Colt.** — The overall ballistic performance of these handgun cartridges was much poorer than that of the .44 Remington Magnum cartridge. They were included in the test because they are commonly owned by many persons working in coastal Alaska and might be carried in the field. With one possible exception, we do not recommend them, even for backup protection. The exception is the .41 Remington Magnum. We were unable to obtain the high-velocity, jacketed 210-gr bullet factory load for our tests. This loading may be suitable for backup use because its ballistics are closer to those of the .44 Remington Magnum than are any of the other cartridges. The .357 S&W Magnum was the best of the other handgun cartridges, but it was much less effective in all categories than the .44 Remington Magnum. The factory bullets of the .44 S&W Special, the .41 Remington Magnum, and the .45 Colt were non-jacketed lead. At their low striking energies, these bullets did not expand. Consequently, penetration was relatively deep. The full-jacketed bullets used in the .45 Auto also penetrated deeply but did not expand.

## Shotgun Cartridge

**12-Gauge × 2¾-Inch Chamber.** — The variety, rapid-fire potential, and reasonable prices of 12-gauge repeating shotguns with short barrels and the impressive appearance of the 1-ounce (438-gr) rifled slug have made this combination popular as a weapon against bears. The slide-action shotgun with a short barrel is relatively light and compact, has good pointing characteristics and a large magazine capacity, and can be fired rapidly. Recoil was similar to that of weapons firing small-caliber magnum rifle cartridges. In our tests, the 12-gauge rifled slug did not have a high overall rank because of the relatively low striking energy and the lack of bullet expansion. The lack of bullet expansion is somewhat misleading. The unfired rifled slug is 0.672 inch in diameter (0.355-in$^2$ area); the 1.7× expansion ratio increases this to a cross-sectional area of 0.62 square inch, which is only slightly smaller than that of the expanded bullets of the .458 Winchester and .460 Weatherby magnum rifle cartridges. The penetration of the rifled slug was good (15.3 inches), and only 4 percent of the unfired weight was lost. No fragmentation occurred. Low energy was due to the low velocity of the slug.

We also tested the penetration of 00 buckshot. The first round was fired at the box from 15 yd. At this range, the nine pellets had a spread of about 12 by 12 inches and a penetration of only 2 to 3 inches. We then shortened the range to 15 ft. From this distance, the spread was 2 inches in diameter, and the maximum penetration of a single shot was 7 inches. At the shorter range, the nine pellets appear to act as a single projectile and the 00 buckshot load might be relatively effective.

From our tests it would appear the slug is much superior to buckshot for protection from bears. Whether buckshot would be lethal to a bear at ranges beyond 5 yd is doubtful. A mixed magazine load of slugs and buckshot can be used, but there appears to be little advantage to this. To be effective, the 12-gauge slugs must be thought of as similar to the bullets in a rifle. Hitting vital areas is the important thing. Hitting a brown bear with a load of buckshot at ranges beyond 5 yd may mean a nonlethal wound and a very angry, active bear.

### A Note on Velocity

Because bullet velocity is an inherent component of bullet energy, it was not one of the factors we used to rank ballistic performance. We did, however, look at its relation to bullet penetration because velocity is the most common single factor used to rank ballistic performance (table 1). In general we found that bullet penetration decreased as striking velocity increased. Notable examples of this were the high-velocity small-bore magnum cartridges, such as the .300 Winchester and .300 Weatherby magnums with lighter weight bullets. The inverse relationship between striking velocity and bullet penetration should be viewed only as a tendency; our data demonstrated considerable variability.

When penetration is compared with striking energy (table 1), the relationship is direct — that is, in general, penetration increases with an increase in energy. Again, the predictive ability of this relationship is poor and should also be considered a tendency. For both striking velocity and energy, the confounding factors appear to be design of the bullet and strength of the bullet materials.

## Recommendations

There is no well-defined distinction between combinations of weapon and ammunition that are adequate or inadequate for protection against bears. The final decision on adequacy must be made by each individual and should include consideration of weapon size and weight, recoil, and the person's experience with firearms. Our data can, however, be used as a general guide to the effectiveness of the weapons and ammunition tested. A rifle in .375 H & H Magnum caliber in the hands of a person who can comfortably tolerate the recoil is a much better choice than a .30-06 or comparable caliber. A .30-06 with 220-gr bullets, however, might be a better choice for a person sensitive to recoil, who may shoot the lighter caliber weapons with more confidence and accuracy.

Based on our tests, four cartridge-bullet combinations appear superior for protection against bears:

- .458 Winchester Magnum, 510-gr soft-point bullet. For a shooter who can handle the recoil of this cartridge, a bolt-action rifle in .458 Winchester Magnum is the surest weapon available.

- .375 H & H Magnum, 300-gr soft-point bullet. The recoil of a rifle in this caliber, although considerably less than that of the .458 Magnum, is still severe for many people. Our tests indicate that the 270-gr soft-point bullet in this caliber is only slightly less effective than the 300-gr bullet and has only slightly less recoil.

- .338 Winchester Magnum, 300-gr bullet. This combination appears to be a good choice. Recoil is somewhat less than that of the .375 Magnum, and our tests indicated that effectiveness would not be much less than that of the .375 Magnum. If the 300-gr bullet cannot be obtained, the 200-gr bullet should be used.

- .30-06, 220-gr bullet. Mild recoil, compared with that of the large- and medium-bore cartridges, even in a lightweight rifle, makes this cartridge a strong contender for shooters who are sensitive to recoil. The .30-06 also has other advantages. It can be found in several rifle actions — bolt, pump (slide), semiautomatic — and can be obtained as, or customized into, a short, handy, lightweight weapon.

Our tests of the performance of bullets at short range were conducted by shooting into a uniform test medium, not into brown bears. The medium did not have a thick, wet coat of hair; thick, resilient skin; dense muscle tissue; or heavy bones; and it was not angry and excited. Consequently, the validity of the tests may not be directly applicable to a real situation involving a bear.

Nevertheless, we believe the tests were a good relative evaluation of bullets shot at short range and can be used to compare different cartridges and bullets. Two major points can be inferred from our tests: (1) none of the many different types of bullets tested was completely adequate, and (2) high striking velocities may not be particularly beneficial at short range. The best results were from bullets relatively heavy for their caliber fired at moderate velocity. Many experienced people have also observed this; we have verified their observations under controlled conditions.

## Design and Use of Rifles for Protection Against Bears

The high-intensity cartridges needed for protection against bears require the use of strong breech mechanisms. The strongest and simplest breech mechanism in a repeating rifle is the bolt action.[6] This section will apply to rifles with that type of action, although many of the comments on stock design, sights, and so forth also apply to rifles with other types of actions.

Several models of bolt-action rifles are available. Of those made in the United States, the Savage Model 110, the Ruger Model 77, the Remington Model 700, and the Winchester Model 70 are the best known. All are turn-bolt operated, magazine fed, and have well-designed trigger mechanisms and safeties. The Savage Model 110 and the Remington Model 700 are available with left-handed actions, but commonly only in .30-06 or smaller calibers. Left-handed .458-, .375-, and .338-caliber rifles might be available on special order. All factory-supplied rifles require modification to increase their suitability for use against bears.

Our tests show fairly similar bullet performance when the same cartridge-bullet weight combination was fired in long- and short-barreled rifles. Most rifles using magnum cartridges have a factory-supplied barrel 24 inches long. These can be shortened to 20 inches for increased portability, with little loss in ballistic performance at short range. This job must be done by a competent gunsmith because the barrel should be cut off in a lathe and the muzzle reshaped (crowned) to insure concentricity.

Cutting off the barrel also requires remounting the ramp that holds the front sight. The ramp should be relocated so its forward end is about three-quarters of an inch from the muzzle. This provides sufficient room to cover the muzzle with a small piece of electrician's tape and to secure this with another piece of tape wrapped around the barrel. Taping the end of the barrel is a worthwhile safety precaution. Bullet performance is not affected; when the rifle is fired, the bullet merely passes through the tape. The tape, however, will prevent any foreign material (mud, duff, rotten wood, vegetation, snow) from entering the muzzle. If the muzzle becomes plugged with this type of material and the rifle is fired, *the barrel may burst.*

Under no circumstances should an attempt be made to clear a plugged barrel by shooting out the plug. The proper way to clear a plugged barrel is to push the plug out with a cleaning rod. Makeshift cleaning rods, such as slender sticks, will usually break off in the barrel. If the plug is not too tight, it may be dislodged by blowing into the barrel — from the breech end is the best way — or by sloshing the barrel in a stream or pool of water. A couple of small pieces of electrician's tape over the muzzle will eliminate the problem of plugs. Taping the muzzle also keeps water from running into the barrel and consequently reduces the possibility of rust.

Because there is almost no possibility of a slung rifle being brought into action during a short-distance confrontation, rifles carried in bear country should not be permanently equipped with slings. The sling should be mounted on detachable swivels, and should be removed when conditions exist for a possible confrontation. The forward sling swivel should be mounted on the barrel about 4 inches in front of the fore-end tip of the stock. This eliminates the possibility of injuring the hand grasping the fore-end of the stock when the rifle is fired, and reduces the amount of barrel projecting over the shoulder when the rifle is slung in the barrel-upward position.

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[6] We do not recommend single-shot rifles for protection from bears because of the time necessary for a followup shot.

If the rifle must be carried by a sling, a barrel-downward position is preferable. The rifle should be slung on the shoulder opposite that from which it is normally fired. A rifle carried in this position can be brought to the firing position by lifting it upward and forward while twisting the wrist so the palm of the hand is up. This is a fast method of getting a slung rifle into firing position. It requires only one hand and can be accomplished in a smooth, coordinated manner with a little practice. In bear country, however, the rifle should be carried unslung in a ready position.

If a bolt-action rifle is used, the bolt should be manipulated while the rifle is in firing position. The rifle should not be lowered from the shoulder to operate the bolt. Learning to operate the bolt from the shoulder requires practice, but the speed and accuracy of subsequent shots are worth the effort.

Some modification of the bolt-action rifle stock is also worthwhile, particularly the length of pull.[7] The pull of factory-stocked rifles is usually too long when the shooter is dressed for the weather conditions of coastal Alaska; a thick wool jacket under a raincoat and backpack will effectively lengthen the pull by more than an inch and make it almost impossible to get the rifle into firing position without catching the butt below the shoulder. This problem is increased by the presence of the rubber recoil pads mounted on almost all heavy-recoiling rifles. A partial remedy is to shorten the length of pull by cutting an inch or more off the butt of the stock and remounting the recoil pad. The degree of shortening depends on the individual. The edges of the remounted recoil pad should be rounded to further minimize the possibility of the rifle's catching on garments or pack straps. A shortened pull also aids in manipulating the bolt while the rifle is shouldered in the firing position.

A further aid to proper bolt operation is to shorten the fore-end of the stock so the left hand (in the case of a right-handed shooter) can be placed around the end of the fore-end rather than along the sides. To do this requires that the left arm be held almost straight out. This is a pointing action and will facilitate proper aiming. By placing the left hand in this manner, the rifle can be held firmly against the shoulder in firing position, with the right hand completely removed from the rifle. The right hand can be freely used to manipulate the bolt and fire the rifle when a person is in this position.

Shooting a rifle when confronted by a bear at close range is similar to shooting a shotgun and has little resemblance to precision marksmanship. The rifle is pointed rather than aimed. This does not mean the sights should be ignored because proper placement of the bullet is paramount. A large-aperture, hunting-style peep sight is an excellent rear sight. The screw-in disk normally provided should be discarded; the remaining aperture can be drilled to a larger diameter if desired. The open, narrow-V or notched rear sights on factory rifles range from poor to very good. Open rear sights are simple and sturdy; however, in a stressful situation, the front sight may not be held completely into the bottom of the notch or V of the rear sight. This causes the rifle to shoot high. For this reason, a low-mounted, simple peep sight may be better. The front sight should be large and have a bright bead or blade so it can be quickly located in dim light, common to the coastal forests of Alaska. The sights must be adjusted to accommodate the user.

Almost all factory rifle stocks are designed for use with telescopic sights. With peep or open sights, the stock comb must be lowered so there is no difficulty in locating the sights when the rifle is in firing position. The cheekpiece found on almost all factory-stocked rifles can be removed. It is mostly an unnecessary cosmetic addition.

Stock modifications must be tailored to the user. This precludes the use of "community" rifles. If possible, a rifle should be issued to an individual and the stock modified to fit. The individual should be held responsible for the care and maintenance of the rifle and should be required to become proficient in its operation. Several stocks of varying dimensions might be kept on hand for use by temporary employees.

The stock modifications listed above are not major alterations and do not require a gunsmith. They can be done by anyone reasonably competent with a few simple woodworking tools. The altered stock should be refinished with an oil or a synthetic finish.

The modifications should be done to all rifles used for protection from bears. If new rifles are to be purchased, it may be better to buy them without stocks and have fiberglass stocks fitted. Several companies produce fiberglass stocks with low combs for use with open or receiver sights. Such stocks are strong, lightweight, warpfree, and impervious to water. They can be broken, but not easily. They can be fitted with recoil pads and studs to accommodate detachable sling swivels. They can also be finished in bright colors, which could aid in finding a misplaced or forgotten rifle or one dropped overboard from a boat. A minor annoyance related to a bright stock might be its attraction for hummingbirds and bees.

Newly ordered rifles should have the metal finished by some process other than hot-rust bluing. Parkerizing or some other rust-resistant surface treatment will not completely eliminate rust but will slow it down. Rifles on hand should also be given this type of finish when the present bluing becomes badly worn or scratched. Rust-proof-finished rifles still need regular cleaning and maintenance.

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[7] Length of pull is the distance from the trigger to the butt of the stock.

Rifle practice should be done throughout the field season. At the minimum, at least one firing session a week should be required. This session should consist of firing at least one full magazine load (three to five shots) while manipulating the bolt from the firing position. Multiple targets should be used: the first at about 20 yd; the second at 15 yd; and the third at 10 yd. At least one shot should be fired at each target, starting with the most distant target and progressing to the nearest target. To some extent, this will simulate shooting at a charging bear. Accuracy standards of one hit in an 8-inch target area on each of the three targets should be sufficient. The rifle should be fired as rapidly as possible, consistent with good placement of the bullet. The latter is more important than rapidity of fire, particularly for the first shot.

Points to be emphasized during practice sessions are:

- The uplift and recoil of the rifle can aid in operating the bolt from the shooting position.

- The bolt must be withdrawn smartly and completely to the rear of its travel to insure ejection of the fired cartridge case so the rifle will not be jammed by a partially ejected cartridge case when the bolt is moved forward into battery.

- The rifle should be held firmly against the shoulder to minimize the recoil felt. A good part of this will be done by the left hand. The extended left arm also absorbs some recoil.

- The shooter should aim the rifle with both eyes open to insure good binocular vision and proper depth perception. This may be difficult for inexperienced persons but can be learned.

- The trigger should be squeezed, not jerked. Modern triggers have a very clean breaking release, and proper trigger manipulation is not hard to learn.

- Because it may not always be possible to bring the rifle to the shoulder to fire it in a normal manner, some practice in "shooting from the hip" may be beneficial. The rifle can be held at or near waist level, pointed at a close (10 yd or less) target, and fired. If possible, the stock should be clamped between the arm and the side of the body. Williams (1952) recommended practice with this shooting position. One of our colleagues was recently required to use the "hip-shooting" position. The bear fell 9 ft from him.

"Dry-firing" practice should be encouraged. The rifle can be moved from a carrying position to the firing position and aimed at rocks and stumps while on the trail. Because the rifle will be carried without a live cartridge in the chamber, this does not constitute a safety hazard.

The brown bear is an extremely interesting animal. Seeing a brown bear at close range is one of the most exciting outdoor experiences a person can have. A mutual withdrawal is the preferred outcome, but this may not always be possible.

The thought of killing a brown bear (or any other wild animal) is repugnant to many people. Whether or not a person will shoot is a personal decision and one that may have to be made quickly. When shooting a bear, the shooter assumes the responsibility of making a quick and clean kill. There should be no desire to hurt or harm the bear, only to avoid being hurt or harmed oneself.

To kill properly, a person needs a knowledge of the anatomy of bears and their reactions after being shot. This information is beyond the scope of this paper, but illustrations of the location of vital organs and bones, as well as written accounts of reactions by bears after being shot, are available (Adams 1976, O'Connor and Goodwin 1961, van Veenen 1975). These should be carefully studied.

Another consideration is that more than one bear may be encountered. Brown bear sows keep their cubs with them for two seasons. A 2-year-old brown bear "cub" is a large bear. Two cubs are not uncommon for brown bears, and triplets and even quadruplets are known to occur.

The most important shot is the first one. If not properly placed, it may also be the last shot fired. If a bear goes down on the first shot, continue to shoot. Do not stop to observe the effects of the shots but continue to aim at vital areas and shoot until the bear stays down and is still. When the bear has stopped moving, reload, work your way around behind the animal, staying as far away as practical and possible, and shoot again into the brain or spine. *Make sure the bear is dead.* If the bear is still active and the rifle is empty, try to avoid the bear, reload, and continue to try to kill it.

## Precautions To Take in Bear Country

A bear that is hit and flees is extremely dangerous. An unwounded bear *can be* a dangerous animal, but a wounded bear *is* a dangerous animal. The wounded bear is dangerous not only to the person who wounded it, but also to others. The shooter has a moral responsibility to find and kill the wounded bear. Following a wounded brown bear in the dense, poorly lighted forest of coastal Alaska is an experience most would like to avoid.

Although the State of Alaska allows bears or other wild animals to be killed to protect life or property, the dead bear is the property of the State (see appendix). The hide, with feet attached, and the skull must be removed and turned over to the Alaska Department of Fish and Game, or the shooter is liable to prosecution and fines. The Department will investigate the kill to determine if a real necessity existed. No part of the bear may be kept.

Firing a warning shot to scare the bear so it will move away has been advocated in print and has been done with success. It may, however, only antagonize the bear and precipitate a charge, or the bear may move away and come back later or from another direction. Again, firing a warning shot is a personal decision; however, a warning shot means there is one less cartridge in the rifle. If a warning shot is fired, another cartridge should be chambered immediately and the magazine reloaded as soon as possible.

The preceding discussion has addressed the final stage of a potentially lethal confrontation between bear and human. In many instances, the ultimate confrontation may be avoided by commonsense precautionary measures:

- Select campsites carefully. Do not pitch a tent in the middle of a well-used bear trail or in a location obviously frequented by bears.

- Keep food out of reach of bears and some distance from camp even when staying in a cabin.

- Precautions for garbage disposal are the same as for food. Do not leave garbage in or close to the camp.

- When walking through bear country, particularly along salmon streams in late summer and early fall, let your presence be known. Keep up a conversation with a companion, or with yourself if alone. A normal or slightly louder tone of voice will usually alert bears to your presence. Some people go a step farther and use noisemaking devices such as bells, whistles, or rocks in a can. This may be a good procedure, but one of the authors has, on two occasions, observed bears that were apparently fascinated by the bell-ringing routine and waited attentively until the noisemakers were in sight (about 30 yd in both instances) before ambling off into the brush. Bears may be attracted to the deer call commonly used in southeast Alaska.

- Be very cautious if a dead animal (deer, moose, bear) is encountered. Bears frequently find a carcass (sometimes in an amazingly short time) and take possession. When packing meat — birds or small game as well as big game — be particularly alert. Try to stay in the open as much as possible, keep a firearm in a ready position, and check your backtrail frequently. If you see a bear obviously homing in on you and you cannot outmaneuver it, you might leave some or all of your load of meat.

- Sows with cubs are particularly aggressive; do not get between them. Bears that are feeding are also more apt to react unfavorably, so give them an especially wide berth.

- A subject of much debate, perhaps second only to the choice of firearm for protection from bears, is the matter of personal hygiene in bear country. What response human odor triggers in a bear may never be known, but reasonable cleanliness is advisable. Women should be aware that changes in body odor during menstruation can be a problem.

Bears want to be left in peace as much as, or more than, humans do. Every once in a while, however, a bear just becomes mean. It may have suffered an injury and be in pain, or it may be old and crotchety, or for any number of reasons it may become aggressive. Then, all your precautions may be useless, and this is the time when you need that thorough familiarization and confidence in yourself and in your weapon.

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## Appendix

The following is reproduced from "Alaska Hunting Regulations No. 23," published by Alaska Board of Game, Alaska Department of Fish and Game:

5 AAC 81.375. TAKING GAME IN DEFENSE OF LIFE OR PROPERTY. (a) Nothing in this chapter prohibits a person from taking game in defense of life or property provided that:

(1) The necessity for the taking is not brought about by harassment or provocation of the animal or an unreasonable invasion of the animal's habitat;

(2) The necessity for taking is not brought about by the improper disposal of garbage or a similar attractive nuisance; and

(3) All other practicable means to protect life and property are exhausted before the game is taken.

(b) Game taken in defense of life or property is the property of the state. Persons taking such game are required to salvage immediately the meat, or in the case of black bear, wolf, wolverine and coyote, the hide must be salvaged and immediately surrendered to the state. In the case of brown, grizzly or polar bear, the hide and skull must be salvaged and surrendered to the state immediately. The department must be notified of such taking immediately and a written report giving the circumstances of the taking of game in defense of life or property must be made to the department within 15 days of such taking.

(c) As used in this section, "Property" is limited to:

(1) dwelling, whether permanent or temporary;

(2) aircraft, boats, automobiles, or other means of conveyance;

(3) domesticated animals; and

(4) other property of substantial value necessary for the livelihood or survival of the owner.

Meehan, William R.; Thilenius, John F. Safety in bear country: protective measures and bullet performance at short range. Gen. Tech. Rep. PNW-152. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1983. 16 p.

Bears are frequently encountered by people working in or enjoying the outdoors. Some government agencies have regulations concerning the firearms their personnel carry for protection against bears.

Guidelines to prevent hazardous encounters with bears are presented, and the performance of commonly used weapons and ammunition is discussed. The ballistic performance of bullets at short range is often considerably different from performance of the same bullet at the longer ranges generally encountered while hunting.

Recommendations are made for weapons and ammunition used as protection from bears.

Keywords: Safety, safety equipment, bears, ballistics, Alaska.

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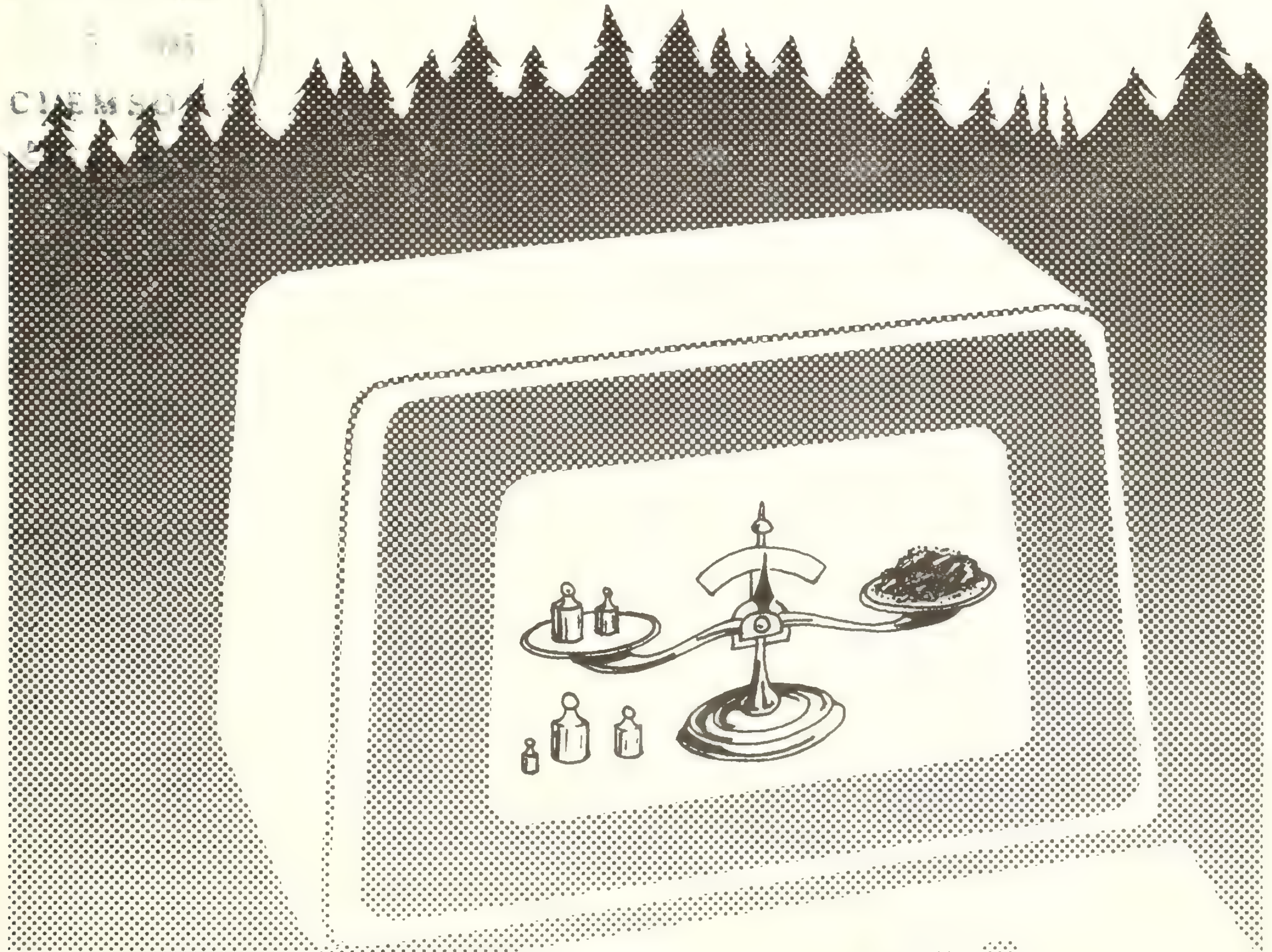
# BDEN: A Timesaving Computer Program for Calculating Soil Bulk Density and Water Content

G. Lynn Starr and J. Michael Geist



## Authors

G. LYNN STARR is a statistical assistant and J. MICHAEL GEIST is a research soil scientist at the Range and Wildlife Habitat Laboratory; Rt. 2, Box 2315; La Grande, OR 97850.

# Abstract

Starr, G. Lynn; Geist, J. Michael. BDEN: a timesaving computer program for calculating soil bulk density and water content. Gen. Tech. Rep. PNW-153. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest And Range Experiment Station; 1983. 12p.

This paper presents an interactive computer program written in BASIC language that will calculate soil bulk density and moisture percentage by weight and volume. Coarse fragment weights are required. The program will also summarize the resulting data giving mean, standard deviation, and 95-percent confidence interval on one or more groupings of data.

Keywords: Soil bulk density, soil water, soil monitoring, computer programs/programing.

# Introduction

Bulk density is commonly used to monitor impacts of management activities on soil conditions. A computer program was developed that computes soil bulk density and moisture content. Its use will save computation time and will reduce errors. BDEN, an interactive program, is written in BASIC language for Jacquard[1] systems. The program listing is provided so modifications can easily be made to suit systems using other languages.

# What the Program Does

Our main objective was to generate individual soil bulk density values. These may come from core samples of fixed or variable volumes. Provision is made in the calculations to adjust for coarse fragment content based on an assumed particle density of 2.65 grams per cubic centimeter (g/cc). Thus, core volume is reduced by coarse fragment volume, leaving only soil volume and weight for computation of soil bulk density.

In addition, if weights of field-moist samples are obtained, soil moisture percentages by both weight and volume can be calculated (based on soil volume and weight adjusted for coarse fragments). This, however, is optional and wet weights are not required for the bulk density calculation.

BDEN will also compute mean, standard deviation, and confidence interval for a user-selected group of observations. The 95-percent probability level was chosen for the confidence interval because it is the value most commonly reported. The program could be altered to allow selection of a different probability level, if desired.

## What Values are Needed

The program uses these values: total core volume (cc), **dry** weights in grams of empty can (can dry wt), can plus coarse fragments (cf) plus soil (total dry wt), and can plus coarse fragments (cf + can dry wt). In addition, total wet weight is needed to calculate percent water. If total wet weight is unavailable, a zero value must be entered so the data following will be read properly.

---

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

## Preparing the File

Following are instructions you will need to prepare for program operation. Before the program can be used, data files, auxiliary files, and the program file must be entered onto computer disc storage.

### Data File Entry

Establish data files using the editor program in your computer. Enter site designation, date, and any other information establishing the identity and field location in the first few lines of the file. Use any format and any number of lines here; however, the last line of this information **must have an asterisk** in the first column.

There **must be two and only two lines for column headings** before data begins. These headings are for the user's convenience only, because the program will skip two lines following the asterisk before reading data. The spelling and spacing of these headings is flexible; however, we have suggested headings that will allow National Forests or Districts the opportunity to standardize labels. Such standardization would avoid confusion when information is exchanged.

Next, enter data values. The first six spaces (columns 1-6) are available for the sample number, followed by one blank and then three spaces (columns 8-10 for class. This class is assigned by the user to provide a simple means of grouping related samples in the summarization process. Class designations may be either numbers or letters. (For example, class could be according to soil type or possibly by plant community.) The rest of the data can be entered free-format (one or more spaces between entries) but must be in the order from left to right specified in the example below (see also table 1):

```
Meadow T.S. 11/80 Unit 25
*Winter logged
  SAMP      CLASS      TOTAL      TOTAL     CF + CAN      CAN        CORE
   NO                 WET WT     DRY WT     DRY WT        WT         VOL
  9-300       A        95.57      72.40      38.50       37.97      58.52
.
.
.
etc.
```

All weights are in grams and core volumes in cubic centimeters. Values may be as precise as you wish, but commonly only one decimal place is necessary. If total wet weights are not available, **do not omit this column,** but enter zero for the wet weight.

### Auxiliary File Entry

The summarization step computes standard deviations and 95-percent confidence intervals. For this step to operate, two auxiliary files must be on your system's nominal disc. (The nominal disc is the one your system "assumes" when no disc designation is included with a filename.) One of these is TTBLE, which is a t-table including values for 2-tailed probabilities of 10, 5, 2, and 1 percent.[2] Values for TTBLE are entered (exactly as shown in table 2) into a file named TTBLE using your computer's edit program. The other file needed is TTABLE, a subprogram that selects the appropriate value from the t-table. Entering and compiling of TTABLE is explained below.

Because TTBLE and TTABLE are referred to in the BDEN program by name, these file names must be spelled exactl as shown here, and they must reside on the nominal disc.

### Program Entry

Using the editor program of your computer, write a file (BDEN.SC in our exan ple) into which you will type the prograr listing, or source code, for BDEN exactl as shown in table 3. The listing must the be translated into binary code, which th computer uses; this requires instructing the computer to compile the source cod as shown below. Compiling need be don only once and is accomplished by enter ing one command line after exiting from the editor program. Assuming the sourc code is in a file named BDEN.SC, the command line would be:

```
$SGBASC BDEN.SC B = BDEN
```

Similarly, the source code for TTABLE (table 4) must be keyed in to a file using the editor and must be compiled. Assun ing the source code for this program is i a file name TTABLE.SC, the command line to compile would be:

```
$SGBASC TTABLE.SC B = TTABLE
```

---

[2] BDEN uses the 5-percent probability level. The additional values are used by TTABLE for other applications.

# Program Use

Once the data file(s), t-table, and compiled program files are on disc, computation may proceed. Simply type BDEN and respond to queries as they appear on the screen.

Your first response should be B to initiate calculation of bulk density, percent water by volume and by weight for each sample in the file. These values are output as new columns added to the original data file on your disc (for example, see table 5). (Percent water values will be zero if zero wet weights were entered.) After exiting BDEN, you may view the data file on the screen to see the results, or print the file using your computer's print program.

Once the computation of bulk density has been done, you may compute the mean, standard deviation, and 95-percent confidence interval by entering a response of M. Output from this summarization step will be appended to the end of a disc file the user has named in response to screen inquiry. (You may exit BDEN and print the output file as mentioned above for the data file. Or you may choose to send the output directly to the printer; for example, respond DPR1 when asked for output filename. If the latter method is used, no copy of the output is saved on disc.)

The next request from the computer is that you indicate which samples are to be included in the mean. You may choose one of three ways to group samples for this step. First, a mean can be computed on an entire file by responding 'ALL' to the request (table 6). Second, a response of 'EACH' will compute a mean for each different class in the file. (For this use, the members of a class **must be consecutive** in the data file.) Or third, certain classes may be grouped by entering the class codes to be selected. For example, a response of 'A' will compute a mean for any sample with class A. A response of 'A' 'D' would compute a single mean for all samples with a class of either A or D (table 7). (Up to eight different classes can be grouped into one mean be this method.) This response **must be surrounded by single or double quotes,** and in the case of two or more classes in the same mean, there must be a blank space between the designated classes.

If you want to compute a mean on sample data entered on two or more files, merge the files into one file via the editor or word-processor program prior to using BDEN.

We would appreciate your correspondence on the usefulness of this program and any suggestions for its improvements.

### Formulas Used:

$$\text{cc soil} = \text{core vol} - \frac{\text{cf} + \text{can dry wt} - \text{can wt}}{2.65}$$

$$\text{g dry soil} = \text{total dry wt} - (\text{cf} + \text{can dry wt})$$

$$\begin{array}{l}\text{\% water content}\\ \quad\text{by volume}\end{array} = \frac{(\text{total wet wt} - \text{total dry wt})}{\text{cc soil}} \times 100$$

$$\begin{array}{l}\text{\% water content}\\ \quad\text{by weight}\end{array} = \frac{(\text{total wet wt} - \text{total dry wt})}{\text{g dry soil}} \times 100$$

$$\begin{array}{l}\text{Bulk}\\ \text{Density}\end{array} = \frac{\text{g dry soil}}{\text{cc soil}}$$

$$\begin{array}{l}\text{Standard}\\ \text{deviation}\end{array} = \sqrt{\frac{\Sigma(X^2) - \frac{(\Sigma X)^2}{n}}{n-1}} \quad \text{where } X = \%H_2O_{(v)} \text{ or } \%H_2O_{(w)} \text{ or BD}$$

$$\begin{array}{l}\text{Confidence}\\ \text{interval}\end{array} = \frac{t_\alpha s}{\sqrt{n}}$$

**Table 1 — Data Entry Set**

MEADOW TS UNIT 25 11/80

*

| SAMP NO. | CLASS | TOTAL WET WT | TOTAL DRY WT | CF + CAN DRY WT | CAN WT | CORE VOL |
|---|---|---|---|---|---|---|
| 9-300 | A | 95.57 | 72.40 | 38.50 | 37.97 | 58.52 |
| 9-301 | A | 88.12 | 70.28 | 38.60 | 38.05 | 58.52 |
| 9-302 | A | 95.35 | 80.90 | 46.10 | 38.82 | 58.52 |
| 9-303 | A | 89.90 | 75.90 | 40.30 | 38.60 | 58.52 |
| 9-304 | A | 113.49 | 93.30 | 42.90 | 38.15 | 58.52 |
| 5-305 | B | 92.62 | 71.45 | 38.60 | 37.98 | 58.52 |
| 5-306 | B | 100.05 | 77.58 | 40.38 | 38.95 | 58.52 |
| 5-307 | B | 103.67 | 80.28 | 38.60 | 37.82 | 58.52 |
| 5-308 | B | 93.96 | 75.35 | 39.92 | 38.95 | 58.52 |
| 5-309 | B | 99.65 | 75.20 | 38.60 | 37.70 | 58.52 |
| 1-310 | C | 97.02 | 77.20 | 40.18 | 39.68 | 58.52 |
| 1-311 | C | 98.79 | 75.30 | 38.28 | 37.35 | 58.52 |
| 1-312 | C | 93.50 | 73.38 | 39.20 | 38.30 | 58.52 |
| 1-313 | C | 92.43 | 72.00 | 38.95 | 38.75 | 58.52 |
| 1-314 | C | 104.37 | 83.71 | 38.15 | 37.30 | 58.52 |
| 3-315 | D | 93.98 | 75.82 | 40.05 | 38.90 | 58.52 |
| 3-316 | D | 82.33 | 66.67 | 39.10 | 38.60 | 58.52 |
| 3-317 | D | 98.10 | 75.03 | 38.25 | 37.75 | 58.52 |
| 3-318 | D | 93.66 | 73.02 | 38.02 | 37.40 | 58.52 |
| 3-319 | D | 97.61 | 75.12 | 39.90 | 38.90 | 58.52 |

**Table 2 — TTBLE**

| | .2 | .1 | .05 | .02 | .01 |
|---|---|---|---|---|---|
| 1 | 3.078 | 6.314 | 12.706 | 31.821 | 63.657 |
| 2 | 1.886 | 2.920 | 4.303 | 6.965 | 9.925 |
| 3 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 |
| 4 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 |
| 5 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 |
| 6 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 |
| 7 | 1.415 | 1.895 | 2.365 | 2.998 | 3.499 |
| 8 | 1.397 | 1.860 | 2.306 | 2.896 | 3.355 |
| 9 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 |
| 10 | 1.372 | 1.812 | 2.223 | 2.764 | 3.169 |
| 11 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 |
| 12 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 |
| 13 | 1.350 | 1.771 | 2.160 | 2.650 | 3.012 |
| 14 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 |
| 15 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 |
| 16 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 |
| 17 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 |
| 18 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 |
| 19 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 |
| 20 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 |
| 21 | 1.323 | 1.721 | 2.080 | 2.518 | 2.831 |
| 22 | 1.321 | 1.717 | 2.074 | 2.508 | 2.819 |
| 23 | 1.319 | 1.714 | 2.069 | 2.500 | 2.807 |
| 24 | 1.318 | 1.711 | 2.064 | 2.492 | 2.797 |
| 25 | 1.316 | 1.708 | 2.060 | 2.485 | 2.787 |
| 26 | 1.315 | 1.706 | 2.056 | 2.479 | 2.779 |
| 27 | 1.314 | 1.703 | 2.052 | 2.473 | 2.771 |
| 28 | 1.313 | 1.701 | 2.048 | 2.467 | 2.763 |
| 29 | 1.311 | 1.699 | 2.045 | 2.462 | 2.756 |
| 30 | 1.310 | 1.697 | 2.042 | 2.457 | 2.750 |
| 99 | 1.282 | 1.645 | 1.960 | 2.326 | 2.576 |

**Table 3 — BDEN Source Code Listing**

```
10      FULL
20      BLKSCN
30      ROLL
40      A$='*',BL$=' ',M$='M',END$='E',ALL$='ALL',EACH$='EACH',BL4$='    '
50      OCLASS$=' ',Z=0,WHAT$=' ',WHERE$=' '
60      STRING CLS(8)
70      PRINT 'TO COMPUTE BULK DENSITY ENTER  B '
80      PRINT 'TO COMPUTE MEAN, S AND CI ENTER  M (MUST HAVE COMPUTED '&
        +'BULK DENSITY PREVIOUSLY)'
90      PRINT 'TO EXIT ENTER  E '
100     INPUT IN IMAGE '#':WHAT$
110     IF SCOMP(WHAT$,END$)=0 THEN GOTO 1320
120     PRINT 'TYPE IN NAME OF INPUT FILE'
130     INPUT IN IMAGE '14#':FILE$
140     OPEN FILE$:F1;ON ERROR GOTO 200
150     IF SCOMP(WHAT$,M$)=0 THEN GOTO 490
160     ON ENDFILE F1 GOTO 390
170     OPEN 'DUMMY',OUTPUT:F2
180     GOSUB 220
190     GOTO 280
200     PRINT 'ERROR ON OPENING FILE - TRY AGAIN'
210     GOTO 130
220               ! INPUT HEADER SUBROUTINE - SEARCHES FOR *
230     INPUT FROM F1 IN IMAGE '80#':HEADER$
240     PRINT ON F2 IN IMAGE '80#':HEADER$
250     IF SCAN(HEADER$,A$,1,V@)<>0 THEN GOTO 270
260     GOTO 230
270     RETURN
280     INPUT FROM F1 IN IMAGE '80#':JUNK$  !  SKIPS COLUMN HEADINGS
290     INPUT FROM F1 IN IMAGE '80#':JUNK$
```

**Table 3 — BDEN Source Code Listing, continued**

```
300     PRINT ON F2 IN IMAGE '74#':' SAMP CLASS  TOTAL   TOTAL   CF+CAN   CAN'&
        +'     CORE   SOIL    BD    %WATER'
310     PRINT ON F2 IN IMAGE '74#':'  NO.        WET WT  DRY WT  DRY WT  DRY '&
        +'WT   VOL    VOL            VOL  WT'
320     INPUT FROM F1 IN IMAGE '6# B 3# B 5F':SNO$,CLASS$,WWT,DWT,GWT,CAN,CORVOL
330     H2O=WWT-DWT,CC=CORVOL-((GWT-CAN)/2.65),H2OV=H2O*100/CC,H2OV=ROUND(H2OV)
340     H2OW=H2O*100/(DWT-GWT),BD=(DWT-GWT)/CC,H2OW=ROUND(H2OW)
350     IF H2O<0 THEN H2OW=0
360     IF H2O<0 THEN H2OV=0
370     PRINT ON F2 IN IMAGE '6# B 3# 6(2B 3%.%%) 2B %.3% B 2(B 3%)':SNO$,&
        CLASS$,WWT,DWT,GWT,CAN,CORVOL,CC,BD,H2OV,H2OW
380     GOTO 320
390     CLOSE F1
400     CLOSE F2
410     LINK '$DELETE ' + FILE$
420     LINK '$RENAME DUMMY ' + FILE$
430     PRINT 'BULK DENSITY COMPUTATIONS COMPLETE'
440     GOTO 70
450     PRINT 'ERROR ON OPENING FILE - TRY AGAIN'
460     GOTO 520
470     IF %ERROR=117 THEN PRINT '** CLASS MUST BE ENCLOSED IN QUOTES **'
475     %ERROR=0
480     GOTO 560
490     ON ENDFILE F1 GOTO 900
500     ON ERROR F1 GOTO 790
510     PRINT 'TYPE IN NAME OF OUTPUT FILE'
520     INPUT IN IMAGE '14#':RESULT$
530     OPEN 'CRT':F3  !  TO ENABLE THE 'ON ERROR' STATEMENT
540     ON ERROR F3 GOTO 470
550     OPEN RESULT$,OUTPUT(MOD):F2;ON ERROR GOTO 450
```

Table 3 — BDEN Source Code Listing, continued

```
560     PRINT 'ENTER CLASSES TO INCLUDE IN MEAN (ENCLOSE EACH CLASS IN '&
        +'QUOTES && SPACE BETWEEN)'
570     PRINT '     ENTER "ALL" TO INCLUDE WHOLE FILE'
580     PRINT '     ENTER "EACH" TO COMPUTE EACH CLASS INDIVIDUALLY'
590     PRINT 'PRESS "RETURN" TO EXIT MEAN COMPUTATION LOOP NOW'
600     CLS=' ',TH2OV=0,TH2OW=0,TBD=0,TSH2OV=0,TSH2OW=0,TSBD=0,N=0
610     INPUT FROM F3 IN IMAGE 'F':CLS
620     IF LENGTH(CLS(1))=0 THEN GOTO 1130
630     GOSUB 220
640     ON DIVCHECK GOTO 820
650     INPUT FROM F1 IN IMAGE '80#':JUNK$ !  SKIPS COLUMN HEADINGS
660     INPUT FROM F1 IN IMAGE '80#':JUNK$
670     CLS(1)=SUBSTR(CLS(1),1,4)
680     IF SCOMP(CLS(1),EACH$)=0 THEN GOTO 1210
690     CLS(1)=SUBSTR(CLS(1),1,3)
700     IF SCOMP(CLS(1),ALL$)=0 THEN GOTO 840
710     INPUT FROM F1 IN IMAGE '7B 3# 50B %.3% B 2(B 3%)':CLASS$,BD,H2OV,H2OW
720     CLASS$=LSPACE(RSPACE(CLASS$))
730     FOR I@=1 TO 8
740     CLS(I@)=SUBSTR(CLS(I@),1,3)
750     IF SCOMP(CLS(I@),CLASS$)=0 THEN GOTO 770
760     NEXT I@
765     GOTO 710
770     GOSUB 870
780     GOTO 710
790     IF %ERROR=117 THEN PRINT '**  ERROR IN DATA FORMAT.  CHECK INPUT FILE **'
795     FOR L@=1 TO 20000
796     NEXT L@
800     %ERROR=0
810     GOTO 1130
```

**Table 3 — BDEN Source Code Listing, continued**

```
820     IF N=0 THEN PRINT '** CLASS NOT FOUND - TRY AGAIN **'

825     %ERROR=0

830     GOTO 1170

840     INPUT FROM F1 IN IMAGE '7B 3# 50B %.3% B 2(B 3%)':CLASS$,BD,H2OV,H2OW

850     GOSUB 870

860     GOTO 840

870     TH2OV=TH2OV+H2OV,TH2OW=TH2OW+H2OW,TBD=TBD+BD,TSH2OV=TSH2OV+H2OV*H2OV

880     TSBD=TSBD+BD*BD,TSH2OW=TSH2OW+H2OW*H2OW,N=N+1

890     RETURN

900     SVS=(TSH2OV-(TH2OV/N)*TH2OV)/(N-1),&

        SWS=(TSH2OW-(TH2OW/N)*TH2OW)/(N-1),&

        SBDS=(TSBD-(TBD/N)*TBD)/(N-1)

910     SV=SQR(SVS),SW=SQR(SWS),SBD=SQR(SBDS)

920     MV=TH2OV/N,MW=TH2OW/N,MBD=TBD/N

930     DF=N-1,ALPHA=.05

940     LINK 'TTABLE',DF,ALPHA,T

950     CIV=T*SV/SQR(N),CIW=T*SW/SQR(N),CIBD=T*SBD/SQR(N)

960     GROUP$=CLS(1)+' '+CLS(2)+' '+CLS(3)+' '+CLS(4)+' '+CLS(5)+' '&

        +CLS(6)+' '+CLS(7)+' '+CLS(8)

970     IF Z=0 THEN GROUP$=RSPACE(GROUP$) ELSE GROUP$=OCLASS$

980                     !  Z IS AN INDEX INDICATING 'EACH' LOOP

990     PRINT ON F2 IN IMAGE '16B  63#':'MEAN   N   STD.DEV.   95% CI FOR '+GROUP$

1000    IM$='14# B 3%.% B 3% 2B 3%.% 6B 3%.%'

1010    PRINT ON F2 IN IMAGE IM$:'% WATER (VOL.)',MV,N,SV,CIV

1020    PRINT ON F2 IN IMAGE IM$:'% WATER (WT.)',MW,N,SW,CIW

1030    PRINT ON F2 IN IMAGE '14# B %.3% B 3% 2B %.3% 6B %.3%':'BULK DENSITY',&

        MBD,N,SBD,CIBD

1040    PRINT ON F2
```

Table 3 — BDEN Source Code Listing, continued

```
1050   IF Z=1 THEN GOTO 1190  ! IF Z=1 THEN 'EACH' LOOP CONTINUES
1060   PRINT 'COMPUTATIONS COMPLETE'
1070   Z=0   ! THIS INDICATES LEAVING 'EACH' LOOP
1080   MBD=0,N=0,SBD=0,CIBD=0
1085   ON ENDFILE F1 GOTO 900
1090   PRINT 'TO COMPUTE DIFFERENT MEAN ON THIS FILE ENTER "M"'
1100   PRINT 'OTHERWISE PRESS "RETURN"'
1110   INPUT IN IMAGE '#':WHERE$
1120   IF SCOMP(WHERE$,M$)=0 THEN GOTO 1170
1130   CLOSE F1
1140   CLOSE F2
1150   CLOSE F3
1160   GOTO 10
1170   REWIND F1
1180   GOTO 560
1190   TH2OV=0,TH2OW=0,TBD=0,TSH2OV=0,TSH2OW=0,TSBD=0,N=0,OCLASS$=CLASS$
1200   GOSUB 870
1210   ON ENDFILE F1 GOTO 1300
1220   Z=1  ! Z IS AN INDEX TO INDICATE 'EACH' LOOP
1230   INPUT FROM F1 IN IMAGE '7B 3# 50B %.3% B 2(B 3%)':CLASS$,BD,H2OV,H2OW
1240   IF SCOMP(OCLASS$,BL$)=0 THEN OCLASS$=CLASS$
1250   IF SCOMP(OCLASS$,CLASS$)<>0 THEN GOTO 900
1260   GOSUB 870
1270   GOTO 1230
1300   Z=2   ! Z=2 INDICATES END OF FILE IN 'EACH' LOOP
1310   GOTO 900
1320   END
```

**Table 4 — TTABLE Source Code Listing**

```
10          GETVAL DF,ALPHA,T
20          IF DF>30 THEN DF=99
30          OPEN   'TTBLE':TVAL
35          INPUT FROM TVAL IN IMAGE '80#':JUNK$
40          INPUT FROM TVAL IN IMAGE '3% B 5(2%.3% B)':DFT,NUM1,&
            NUM2,NUM3,NUM4,NUM5
50          IF DFT<DF THEN GOTO 40
55          IF ALPHA=.2 THEN T=NUM1
60          IF ALPHA=.1 THEN T=NUM2
70          IF ALPHA=.05 THEN T=NUM3
80          IF ALPHA=.02 THEN T=NUM4
90          IF ALPHA=.01 THEN T=NUM5
100         CLOSE TVAL
110         STOP
```

**Table 5 — Data Computation Results:**

```
MEADOW TS UNIT 25 11/80
*
SAMP    CLASS    TOTAL    TOTAL    CF+CAN    CAN    CORE    SOIL     BD      %WATER
 NO.            WET WT   DRY WT    DRY WT     WT    VOL     VOL              VOL  WT
9-300     A      95.57    72.40     38.50   37.97   58.52   58.32   0.581     39  68
9-301     A      88.12    70.28     38.60   38.05   58.52   58.31   0.543     30  56
9-302     A      95.35    80.90     46.10   38.82   58.52   55.77   0.624     25  41
9-303     A      89.90    75.90     40.30   38.60   58.52   57.88   0.615     24  39
9-304     A     113.49    93.30     42.90   38.15   58.52   56.73   0.888     35  40
5-305     B      92.62    71.45     38.60   37.98   58.52   58.29   0.564     36  64
5-306     B     100.05    77.58     40.38   38.95   58.52   57.98   0.642     38  60
5-307     B     103.67    80.28     38.60   37.82   58.52   58.23   0.716     40  56
5-308     B      93.96    75.35     39.92   38.95   58.52   58.15   0.609     32  52
5-309     B      99.65    75.20     38.60   37.70   58.52   58.18   0.629     42  66
1-310     C      97.02    77.20     40.18   39.68   58.52   58.33   0.635     33  53
1-311     C      98.79    75.30     38.28   37.35   58.52   58.17   0.636     40  63
1-312     C      93.50    73.38     39.20   38.30   58.52   58.18   0.587     34  58
1-313     C      92.43    72.00     38.95   38.75   58.52   58.44   0.565     34  61
1-314     C     104.37    83.71     38.15   37.30   58.52   58.20   0.783     35  45
3-315     D      93.98    75.82     40.05   38.90   58.52   58.09   0.616     31  50
3-316     D      82.33    66.67     39.10   38.60   58.52   58.33   0.473     26  56
3-317     D      98.10    75.03     38.25   37.75   58.52   58.33   0.631     39  62
3-318     D      93.66    73.02     38.02   37.40   58.52   58.29   0.600     35  58
3-319     D      97.61    75.12     39.90   38.90   58.52   58.14   0.606     38  63
```

**Table 6 — Data Summary for Entire File**

MEADOW TS UNIT 25 11/80

| | MEAN | N | STD.DEV. | 95% CI FOR ALL |
|---|---|---|---|---|
| % WATER (VOL.) | 34.3 | 20 | 5.1 | 2.4 |
| % WATER (WT.) | 55.6 | 20 | 8.7 | 4.1 |
| BULK DENSITY | 0.627 | 20 | 0.087 | 0.041 |

**Table 7 — Data Summary for a Class**

MEADOW TS UNIT 25 11/80

| | MEAN | N | STD.DEV. | 95% CI FOR A D |
|---|---|---|---|---|
| % WATER (VOL.) | 32.2 | 10 | 5.8 | 4.2 |
| % WATER (WT.) | 53.3 | 10 | 10.4 | 7.4 |
| BULK DENSITY | 0.618 | 10 | 0.106 | 0.076 |

Starr, G. Lynn; Geist, J. Michael. BDEN: a timesaving computer program for calculating soil bulk density and water content. Gen. Tech. Rep. PNW-153. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest And Range Experiment Station; 1983. 12p.

This paper presents an interactive computer program written in BASIC language that will calculate soil bulk density and moisture percentage by weight and volume. Coarse fragment weights are required. The program will also summarize the resulting data giving mean, standard deviation, and 95-percent confidence interval on one or more groupings of data.

Keywords: Soil bulk density, soil water, soil monitoring, computer programs/programing.

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

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Pacific Northwest Forest and Range
Experiment Station
809 NE Sixth Avenue
Portland, Oregon 97232